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ANALYSIS AND CONTROL OF THERMAL POLLUTION

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August 1974

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ANALYSIS AND CONTROL OF THERMAL POLLUTION

This course is designed for professional personnel concerned with the monitoring, evaluation, and control of temperature changes in water bodies.

U. S. ENVIRONMENTAL PROTECTION AGENCY
Water Program Operations

TRAINING PROGRAM

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CONTENTS

Title or Description	Outline Number
The Aquatic Environment	1
Water Resources and Needs	2
Techniques for the Biological Evaluation of Pollutants	3
Significance of "Limiting Factors" to Population Variation	4
The Advent of Thermal Pollution	5
General Effects of Temperature on Aquatic Organisms	6
Physical and Chemical Effects of Water Temperature	7
Effects of Thermal Pollution on Microorganisms	8
Effects of Thermal Pollution on Primary Producers	9
Effects of Thermal Pollution on the Benthos	10
Effects of Thermal Pollution on Fish Life	11
Thermal Acclimation of Aquatic Organisms	12
The Influence of Temperature on Behavior of Fish	13
Effects of Temperature on Reproduction and Growth	14
Temperature Requirements of Centrarchids	15
Potential Effects of Thermal Pollution to Pacific Salmon	16
Effects of Temperature on Pacific Salmon	17
Research on Thermal Effects: Fish	18
Beneficial Effects of Heat Additions	19
Thermal Pollution From Natural Causes	20
Thermal Pollution Resulting from Man's Physical Alterations of the Environment	21
Industrial Sources of Thermal Pollution	22
Biological Monitoring of Heated Lakes and Streams	23

Title or Description	Outline Number
Data Requirements, Field Studies, and Instrumentation for Temperature Prediction	24
Summary Outline of Current Theories Relating to Temperature Prediction in a Body of Water	25
Dissipation of Heat in a Body of Water	26
The Conservation of Heat in a Body of Water--The Energy Budget Approach to Water Temperature Prediction	27
The Energy Budget Approach to Water Temperature Prediction Example Problem	28
Prediction of Water Temperatures in Rivers and Streams--The Exponential Decay of Transient Temperatures	29
Water Temperature and Prediction - Bibliography	30
Thermal Pollution Control Methods	31

THE AQUATIC ENVIRONMENT

Part 1: The Nature and Behavior of Water

I INTRODUCTION

The earth is physically divisible into the lithosphere or land masses, and the hydrosphere which includes the oceans, lakes, streams, and subterranean waters.

A Upon the hydrospere are based a number of sciences which represent different approaches. Hydrology is the general science of water itself with its various special fields such as hydrography, hydraulics, etc. These in turn merge into physical chemistry and chemistry.

B Limnology and oceanography combine aspects of all of these, and deal not only with the physical liquid water and its various naturally occurring solutions and forms, but also with living organisms and the infinite interactions that occur between them and their environment.

C Water quality management, including pollution control, thus looks to all branches of aquatic science in efforts to coordinate and improve man's relationship with his aquatic environment.

II SOME FACTS ABOUT WATER

A Water is the only abundant liquid on our planet. It has many properties most unusual for liquids, upon which depend most of the familiar aspects of the world about us as we know it. (See Table 1)

TABLE 1

UNIQUE PROPERTIES OF WATER

Property	Significance
Highest heat capacity (specific heat) of any solid or liquid (except NH_3)	Stabilizes temperatures of organisms and geographical regions
Highest latent heat of fusion (except NH_3)	Thermostatic effect at freezing point
Highest heat of evaporation of any substance	Important in heat and water transfer of atmosphere
The only substance that has its maximum density as a liquid (4°C)	Fresh and brackish waters have maximum density above freezing point. This is important in vertical circulation pattern in lakes.
Highest surface tension of any liquid	Controls surface and drop phenomena, important in cellular physiology
Dissolves more substances in greater quantity than any other liquid	Makes complex biological system possible. Important for transportation of materials in solution.
Pure water has the highest di-electric constant of any liquid	Leads to high dissociation of inorganic substances in solution
Very little electrolytic dissociation	Neutral, yet contains both H^+ and OH^- ions
Relatively transparent	Absorbs much energy in infra red and ultra violet ranges, but little in visible range. Hence "colorless"

B Physical Factors of Significance

1 Water substance

Water is not simply "H_2O" but in reality is a mixture of some 33 different substances involving three isotopes each of hydrogen and oxygen (ordinary hydrogen H^1, deuterium H^2, and tritium H^3; ordinary oxygen O^{16}, oxygen 17, and oxygen 18) plus 15 known types of ions. The molecules of a water mass tend to associate themselves as polymers rather than to remain as discrete units. (See Figure 1)

SUBSTANCE OF PURE WATER

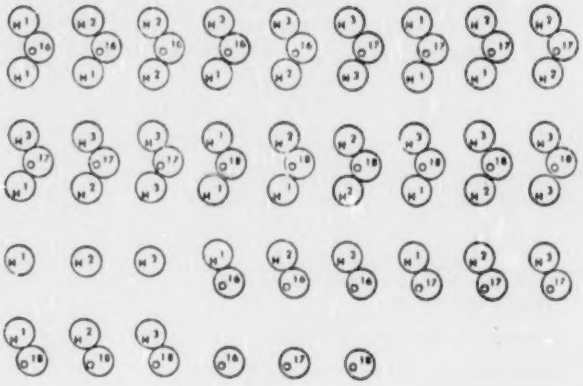

Figure 1

2 Density

a Temperature and density: Ice. Water is the only known substance in which the solid state will float on the liquid state. (See Table 2)

TABLE 2

EFFECTS OF TEMPERATURE ON DENSITY OF PURE WATER AND ICE*

Temperature (°C)	Density	
	Water	Ice**
-10	.99815	.9397
- 8	.99869	.9360
- 6	.99912	.9020
- 4	.99945	.9277
- 2	.99970	.9229
0	.99987----	.9168
2	.99997	
4	1.00000	
6	.99997	
8	.99988	
10	.99973	
20	.99823	
40	.99225	
60	.98324	
80	.97183	
100	.95838	

* Tabular values for density, etc., represent estimates by various workers rather than absolute values, due to the variability of water.

** Regular ice is known as "ice I". Four or more other "forms" of ice are known to exist (ice II, ice III, etc.), having densities at 1 atm. pressure ranging from 1.1595 to 1.67. These are of extremely restricted occurrence and may be ignored in most routine operations.

This ensures that ice usually forms on top of a body of water and tends to insulate the remaining water mass from further loss of heat. Did ice sink, there could be little or no carryover of aquatic life from season to season in the higher latitudes. Frazil or needle ice forms colloidally at a few thousandths of a degree below 0° C. It is adhesive and may build up on submerged objects as "anchor ice", but it is still typical ice (ice I).

1) Seasonal increase in solar radiation annually warms surface waters in summer while other factors result in winter cooling. The density differences resulting establish two classic layers: the epilimnion or surface layer, and the hypolimnion or lower layer, and in between is the thermocline or shear-plane.

2) While for certain theoretical purposes a "thermocline" is defined as a zone in which the temperature changes one degree centigrade for each meter of depth, in practice, any transitional layer between two relatively stable masses of water of different temperatures may be regarded as a thermocline.

3) Obviously the greater the temperature differences between epilimnion and hypolimnion and the sharper the gradient in the thermocline, the more stable will the situation be.

4) From information given above, it should be evident that while the temperature of the hypolimnion rarely drops much below 4° C, the epilimnion may range from 0° C upward.

5) When epilimnion and hypolimnion achieve the same temperature, stratification no longer exists. The entire body of water behaves hydrologically as a unit, and tends to assume uniform chemical and physical characteristics. Even a light breeze may then cause the entire body of water to circulate. Such events are called overturns, and usually result in water quality changes of considerable physical, chemical, and biological significance. Mineral-rich water from the hypolimnion, for example, is mixed with oxygenated water from the epilimnion. This usually triggers a sudden growth or "bloom" of plankton organisms.

6) When stratification is present, however, each layer behaves relatively independently, and significant quality differences may develop.

7) Thermal stratification as described above has no reference to the size of the water mass; it is found in oceans and puddles.

b The relative densities of the various isotopes of water influence its molecular composition. For example, the lighter O_{16} tends to go off first in the process of evaporation, leading to the relative enrichment of air by O_{16} and the enrichment of water by O_{17} and O_{18}. This can lead to a measurably higher O_{18} content in warmer climates. Also, the temperature of water in past geologic ages can be closely estimated from the ratio of O_{18} in the carbonate of mollusc shells.

c Dissolved and/or suspended solids may also affect the density of natural water masses (see Table 3)

TABLE 3
EFFECTS OF DISSOLVED SOLIDS ON DENSITY

Dissolved Solids (Grams per liter)	Density (at 4°C)
0	1.00000
1	1.00085
2	1.00169
3	1.00251
10	1.00818
35 (mean for sea water)	1.02822

d Types of density stratification

1) Density differences produce stratification which may be permanent, transient, or seasonal.

2) Permanent stratification exists for example where there is a heavy mass of brine in the deeper areas of a basin which does not respond to seasonal or other changing conditions.

3) Transient stratification may occur with the recurrent influx of tidal water in an estuary for example, or the occasional influx of cold muddy water into a deep lake or reservoir.

4) Seasonal stratification is typically thermal in nature, and involves the annual establishment of the epilimnion, hypolimnion, and thermocline as described above.

5) Density stratification is not limited to two-layered systems; three, four, or even more layers may be encountered in larger bodies of water.

e A "plunge line" (sometimes called "thermal line") may develop at the mouth of a stream. Heavier water flowing into a lake or reservoir plunges below the lighter water mass of the epiliminium to flow along at a lower level. Such a line is usually marked by an accumulation of floating debris.

f Stratification may be modified or entirely suppressed in some cases when deemed expedient, by means of a simple air lift.

3 The viscosity of water is greater at lower temperatures (see Table 4).

This is important not only in situations involving the control of flowing water as in a sand filter, but also since overcoming resistance to flow generates heat, it is significant in the heating of water by internal friction from wave and current action. Living organisms more easily support themselves in the more viscous (and also denser) cold waters of the arctic than in the less viscous warm waters of the tropics. (See Table 4).

TABLE 4

VISCOSITY OF WATER (In millipoises at 1 atm)

	Dissolved solids in g/L			
Temp. ° C	0	5	10	30
-10	26.0	----	----	----
- 5	21.4	----	----	----
0	17.94	18.1	18.24	18.7
5	15.19	15.3	15.5	16.0
10	13.10	13.2	13.4	13.8
30	8.00	8.1	8.2	8.6
100	2.84	----	----	----

4 Surface tension has biological as well as physical significance. Organisms whose body surfaces cannot be wet by water can either ride on the surface film or in some instances may be "trapped" on the surface film and be unable to re-enter the water.

5 Heat or energy

Incident solar radiation is the prime source of energy for virtually all organic and most inorganic processes on earth. For the earth as a whole, the total amount (of energy) received annually must exactly balance that lost by reflection and radiation into space if climatic and related conditions are to remain relatively constant over geologic time.

a For a given body of water, immediate sources of energy include in addition to solar irradiation: terrestrial heat, transformation of kinetic energy (wave and current action) to heat, chemical and biochemical reactions, convection from the atmosphere, and condensation of water vapor.

b The proportion of light reflected depends on the angle of incidence, the temperature, color, and other qualities of the water; and the presence or absence of films of lighter liquids such as oil. In general, as the depth increases arithmetically, the light tends to decrease geometrically. Blues, greens, and yellows tend to penetrate most deeply while ultra violet, violets, and orange-reds are most quickly absorbed. On the order of 90% of the total illumination which penetrates the surface film is absorbed in the first 10 meters of even the clearest water, thus tending to warm the upper layers.

6 Water movements

a Waves or rhythmic movement

1) The best known are traveling waves caused by wind. These are effective only against objects near the surface. They have little effect on the movement of large masses of water.

2) Seiches

Standing waves or seiches occur in lakes, estuaries, and other enclosed bodies of water, but are seldom large enough to be observed. An "internal wave or seich" is an oscillation in a submersed mass of water such as a hypolimnion, accompanied by compensating oscillation in the overlying water so that no significant change in surface level is detected. Shifts in submerged water masses of this type can have severe effects on the biota and also on human water uses where withdrawals are confined to a given depth. Descriptions and analyses of many other types and sub-types of waves and wave-like movements may be found in the literature.

b Tides

1) Tides are the longest waves known, and are responsible for the once or twice a day rythmic rise and fall of the ocean level on most shores around the world.

2) While part and parcel of the same phenomenon, it is often convenient to refer to the rise and fall of the water level as "tide," and to the resulting currents as "tidal currents."

3) Tides are basically caused by the attraction of the sun and moon on water masses, large and small; however, it is only in the oceans and possibly certain of the larger lakes that true tidal action has been demonstrated. The patterns of tidal action are enormously complicated by local topography, interaction with seiches, and other factors. The literature on tides is very large.

c Currents (except tidal currents) are steady arythmic water movements which have had major study only in oceanography although they are most often observed in rivers and streams. They are primarily concerned with the translocation of water masses. They may be generated internally by virtue of density changes, or externally by wind or terrestrial topography. Turbulence phenomena or eddy currents are largely responsible for lateral mixing in a current. These are of far more importance in the economy of a body of water than mere laminar flow.

d **Coriolis** force is a result of interaction between the rotation of the earth, and the movement of masses or bodies on the earth. The net result is a slight tendency for moving objects to veer to the right in the northern hemisphere, and to the left in the southern hemisphere. While the result in fresh waters is usually negligible, it may be considerable in marine waters. For example, other factors permitting, there is a tendency in estuaries for fresh waters to move toward the ocean faster along the right bank, while salt tidal waters tend to intrude farther inland along the left bank. Effects are even more dramatic in the open oceans.

e **Langmuir circulation** (or L. spirals) is the interlocking rotation of somewhat cylindrical masses of surface water under the influence of wind action. The axes of the cylinders are parallel to the direction of the wind.

To somewhat oversimplify the concept, a series of adjoining cells might be thought of as chains of interlocking gears in which at every other contact the teeth are rising while at the alternate contacts, they are sinking (Figure 2).

The result is elongated masses of water rising or sinking together. This produces the familiar "wind rows" of foam, flotsam and jetsam, or plankton often seen streaking windblown lakes or oceans. Certain zoo-plankton struggling to maintain a position near the surface tend to collect in the down current between two Langmuir cells, causing such an area to be called the "red dance", while the clear upwelling water between is the "blue dance".

This phenomenon may be important in water or plankton sampling on a windy day.

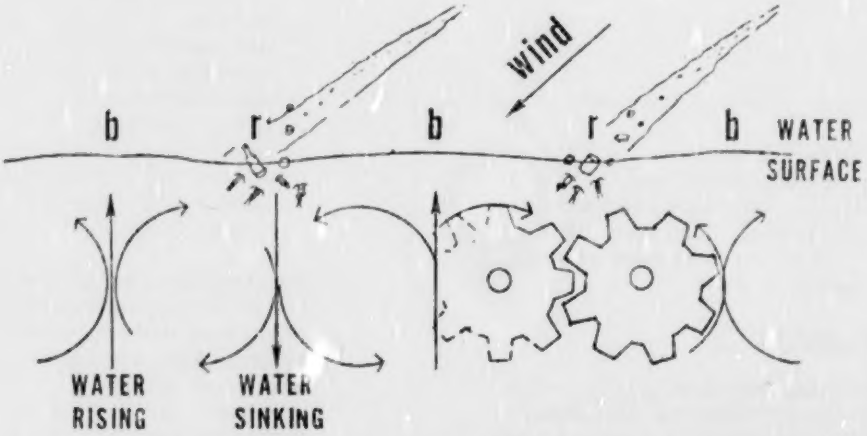

Figure 2. Langmuire Spirals
b. Blue dance, water rising. r. Red dance, water sinking, floating or swimming objects concentrated.

6 The pH of pure water has been determined between 5.7 and 7.01 by various workers. The latter value is most widely accepted at the present time. Natural waters of course vary widely according to circumstances.

C The elements of hydrology mentioned above represent a selection of some of the more conspicuous physical factors involved in working with water quality. Other items not specifically mentioned include: molecular structure of waters, interaction of water and radiation, internal pressure, acoustical characteristics, pressure-volume-temperature relationships, refractivity, luminescence, color, dielectrical characteristics and phenomena, solubility, action and interactions of gases, liquids and solids, water vapor, phenomena of hydrostatics and hydrodynamics in general.

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Descriptors:
Aquatic Environment, Estuarine Environment, Lentic Environment, Lotic Environment, Currents, Marshes, Limnology, Water Properties

THE AQUATIC ENVIRONMENT

Part 2: The Aquatic Environment as an Ecosystem

I INTRODUCTION

Part 1 introduced the lithosphere and the hydrosphere. Part 2 will deal with certain general aspects of the biosphere, or the sphere of life on this earth, which photographs from space have shown is a finite globe in infinite space.

This is the habitat of man and the other organisms. His relationships with the aquatic biosphere are our common concern.

II THE BIOLOGICAL NATURE OF THE WORLD WE LIVE IN

A We can only imagine what this world must have been like before there was life.

B The world as we know it is largely shaped by the forces of life.

1 Primitive forms of life created organic matter and established soil.

2 Plants cover the lands and enormously influence the forces of erosion.

3 The nature and rate of erosion affect the redistribution of materials (and mass) on the surface of the earth (topographic changes).

4 Organisms tie up vast quantities of certain chemicals, such as carbon and oxygen.

5 Respiration of plants and animals releases carbon dioxide to the atmosphere in influential quantities.

6 CO_2 affects the heat transmission of the atmosphere.

C Organisms respond to and in turn affect their environment. Man is one of the most influential.

III ECOLOGY IS THE STUDY OF THE INTERRELATIONSHIPS BETWEEN ORGANISMS, AND BETWEEN ORGANISMS AND THEIR ENVIRONMENT.

A The ecosystem is the basic functional unit of ecology. Any area of nature that includes living organisms and nonliving substances interacting to produce an exchange of materials between the living and nonliving parts constitutes an ecosystem. (Odum, 1959)

1 From a structural standpoint, it is convenient to recognize four constituents as composing an ecosystem (Figure 1).

a Abiotic NUTRIENT MINERALS which are the physical stuff of which living protoplasm will be synthesized.

b Autotrophic (self-nourishing) or PRODUCER organisms. These are largely the green plants (holophytes), but other minor groups must also be included (See Figure 2). They assimilate the nutrient minerals, by the use of considerable energy, and combine them into living organic substance.

c Heterotrophic (other-nourishing) CONSUMERS (holozoic), are chiefly the animals. They ingest (or eat) and digest organic matter, releasing considerable energy in the process.

d Heterotrophic REDUCERS are chiefly bacteria and fungi that return complex organic compounds back to the original abiotic mineral condition, thereby releasing the remaining chemical energy.

2 From a functional standpoint, an ecosystem has two parts (Figure 2)

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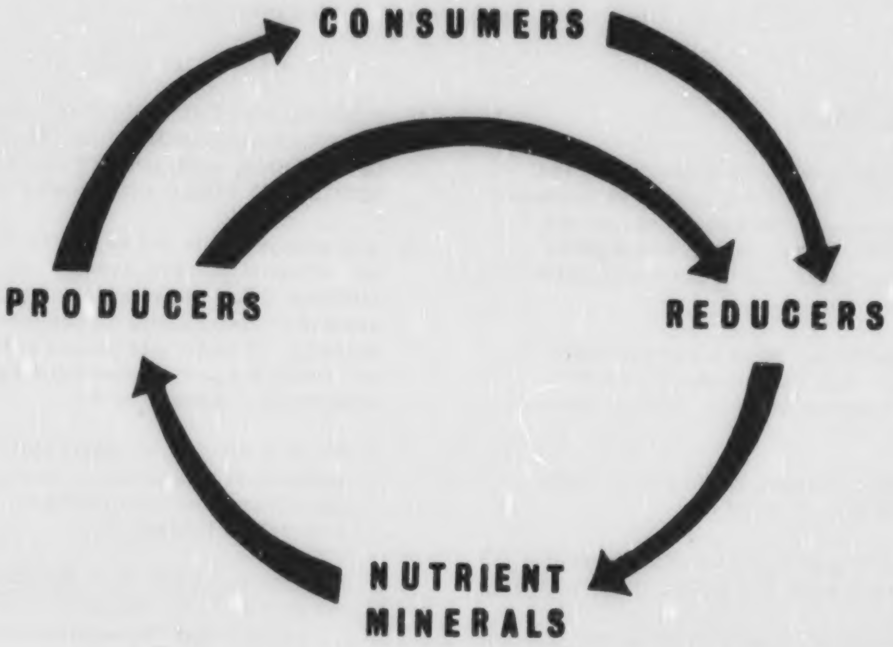

FIGURE 1

a The autotrophic or producer organisms, which construct organic substance.

b The heterotrophic or consumer and reducer organisms which destroy organic substance.

3 Unless the autotrophic and heterotrophic phases of the cycle approximate a dynamic equilibrium, the ecosystem and the environment will change.

B Each of these groups includes simple, single-celled representatives, persisting at lower levels on the evolutionary stems of the higher organisms. (Figure 2)

1 These groups span the gaps between the higher kingdoms with a multitude of transitional forms. They are collectively called the PROTISTA.

2 Within the protista, two principal subgroups can be defined on the basis of relative complexity of structure.

a The bacteria and blue-green algae, lacking a nuclear membrane may be considered as the lower protista (or Monera).

b The single-celled algae and protozoa are best referred to as the Higher Protista.

C Distributed throughout these groups will be found most of the traditional "phyla" of classic biology.

IV FUNCTIONING OF THE ECOSYSTEM

A A food chain is the transfer of food energy from plants through a series of organisms with repeated eating and being eaten. Food chains are not isolated sequences but are interconnected.

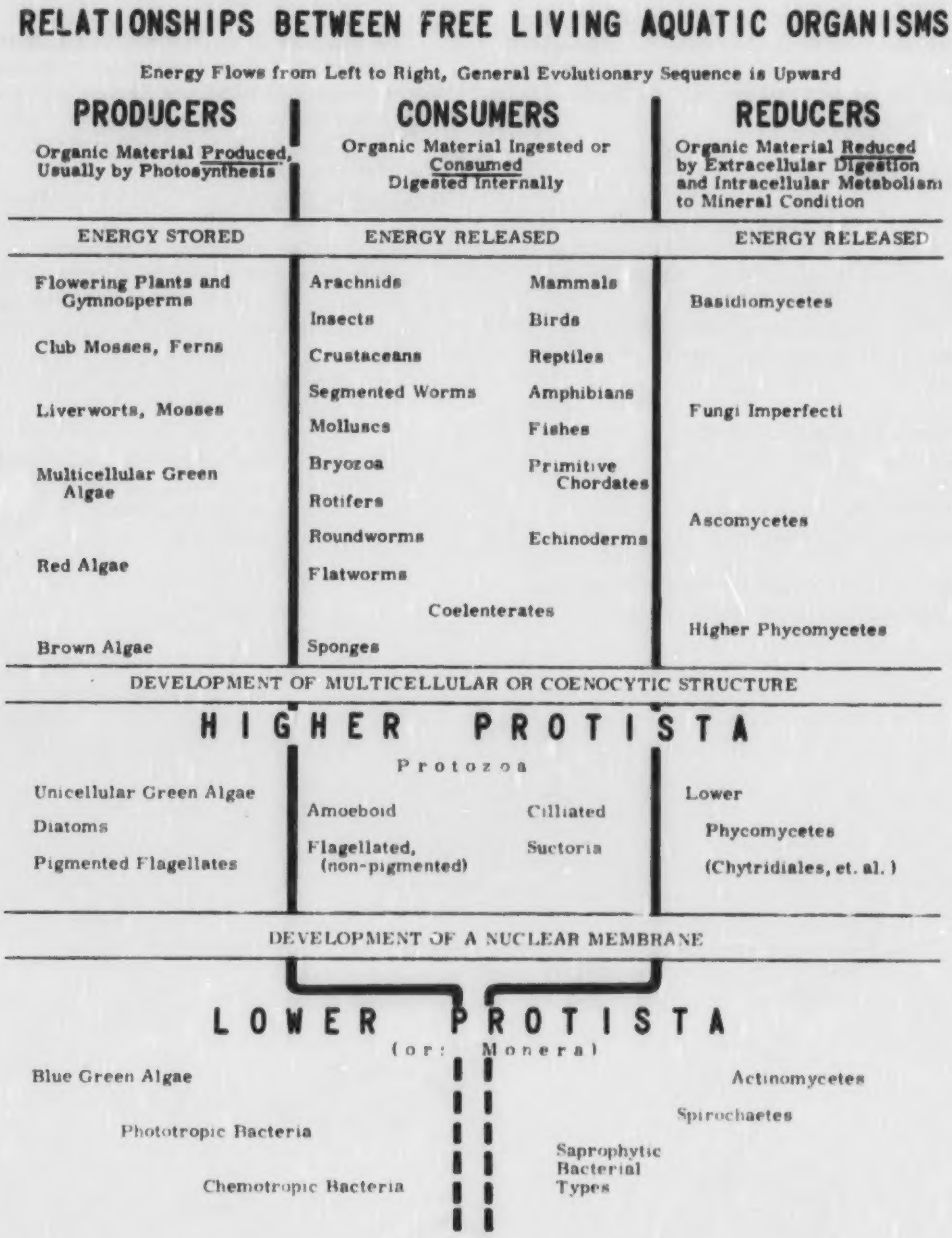
RELATIONSHIPS BETWEEN FREE LIVING AQUATIC ORGANISMS
Energy Flows from Left to Right, General Evolutionary Sequence is Upward
PRODUCERS
Organic Material Produced, Usually by Photosynthesis
CONSUMERS
Organic Material Ingested or Consumed Digested Internally
REDUCERS
Organic Material Reduced by Extracellular Digestion and Intracellular Metabolism to Mineral Condition
ENERGY STORED
ENERGY RELEASED
ENERGY RELEASED
Flowering Plants and Gymnosperms
Club Mosses, Ferns
Liverworts, Mosses
Multicellular Green Algae
Red Algae
Brown Algae
Arachnids
Insects
Crustaceans
Segmented Worms
Molluscs
Bryozoa
Rotifers
Roundworms
Flatworms
Coelenterates
Sponges
Mammals
Birds
Reptiles
Amphibians
Fishes
Primitive Chordates
Echinoderms
Basidiomycetes
Fungi Imperfecti
Ascomycetes
Higher Phycomycetes
DEVELOPMENT OF MULTICELLULAR OR COENOCYTIC STRUCTURE
HIGHER PROTISTA
Protozoa
Unicellular Green Algae
Diatoms
Pigmented Flagellates
Amoeboid
Flagellated, (non-pigmented)
Ciliated
Suctoria
Lower Phycomycetes (Chytridiales, et. al.)
DEVELOPMENT OF A NUCLEAR MEMBRANE
LOWER PROTISTA
(or: Monera)
Blue Green Algae
Phototropic Bacteria
Chemotropic Bacteria
Actinomycetes
Spirochaetes
Saprophytic Bacterial Types

FIGURE 2

BI ECO pl 2a. 1. 69

B A food web is the interlocking pattern of food chains in an ecosystem. (Figures 3, 4) In complex natural communities, organisms whose food is obtained by the same number of steps are said to belong to the same trophic (feeding) level.

C Trophic Levels

1 First - Green plants (producers) (Figure 5) fix biochemical energy and synthesize basic organic substances. This is "primary production".

2 Second - Plant eating animals (herbivores) depend on the producer organisms for food.

3 Third - Primary carnivores, animals which feed on herbivores.

4 Fourth - Secondary carnivores feed on primary carnivores.

5 Last - Ultimate carnivores are the last or ultimate level of consumers.

D Total Assimilation

The amount of energy which flows through a trophic level is distributed between the production of biomass (living substance), and the demands of respiration (internal energy use by living organisms) in a ratio of approximately 1:10.

E Trophic Structure of the Ecosystem

The interaction of the food chain phenomena (with energy loss at each transfer) results in various communities having definite trophic structure or energy levels. Trophic structure may be measured and described either in terms of the standing crop per unit area or in terms of energy fixed per unit area per unit time at successive trophic levels. Trophic structure and function can be shown graphically by means of ecological pyramids (Figure 5).

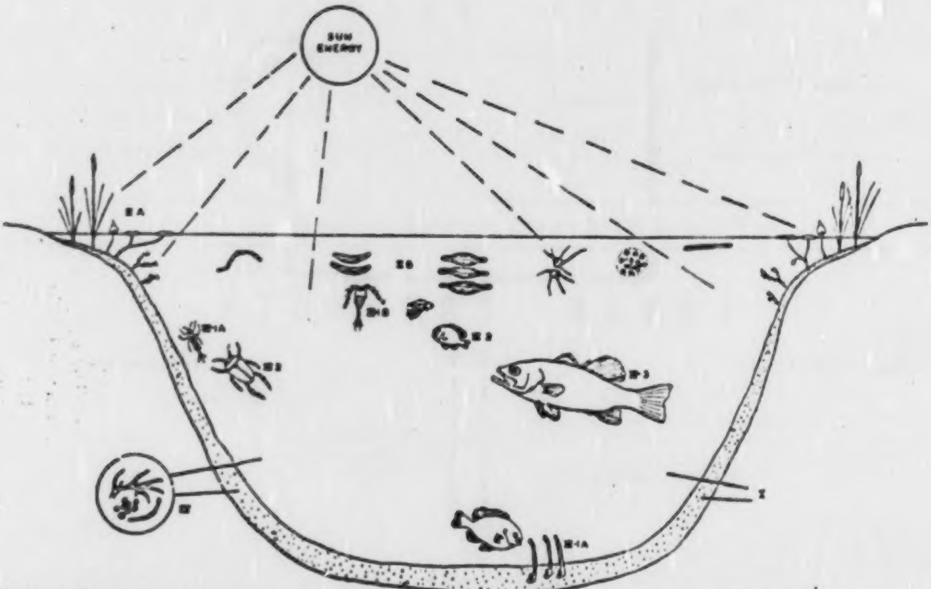

Figure 3. Diagram of the pond ecosystem. Basic units are as follows: I, abiotic substances–basic inorganic and organic compounds; IIA, producers–rooted vegetation; IIB, producers–phytoplankton; III-1A, primary consumers (herbivores)–bottom forms; III-1B, primary consumers (herbivores)–zooplankton; III-2, secondary consumers (carnivores); III-3, tertiary consumers (secondary carnivores); IV, decomposers–bacteria and fungi of decay.

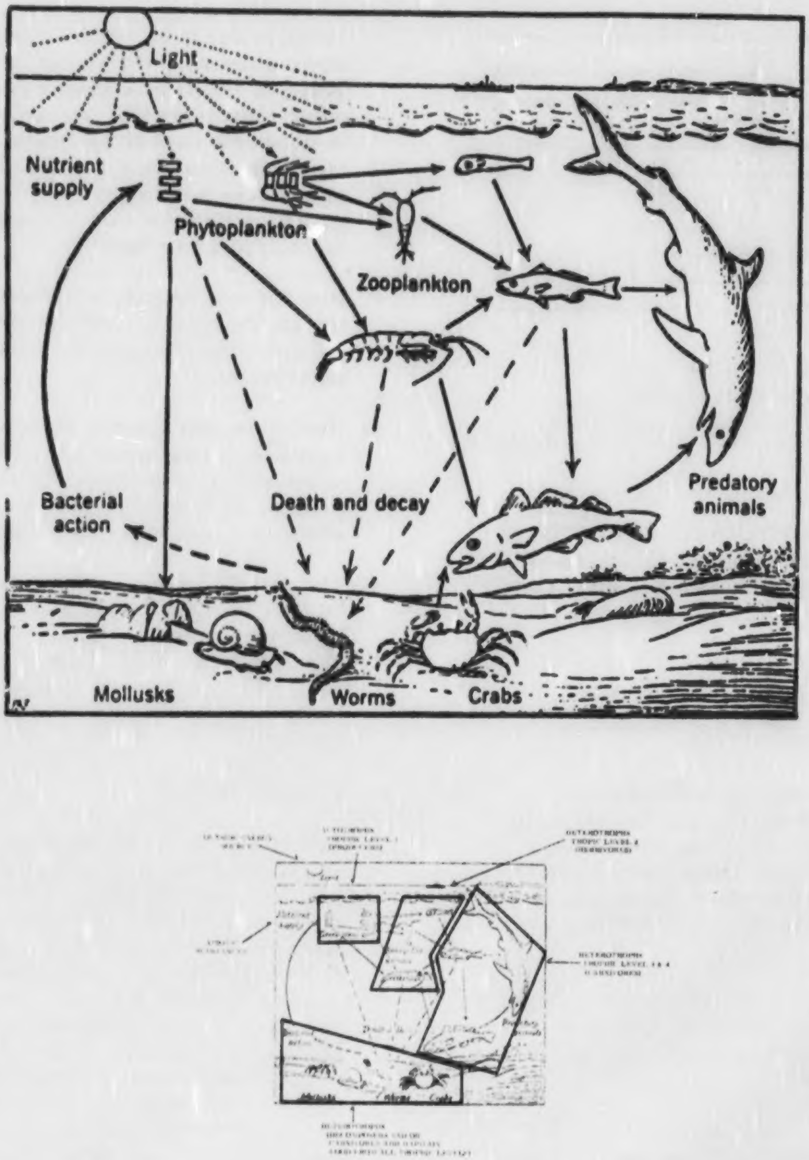

Figure 4. A MARINE ECOSYSTEM (After Clark, 1954 and Patten, 1966)

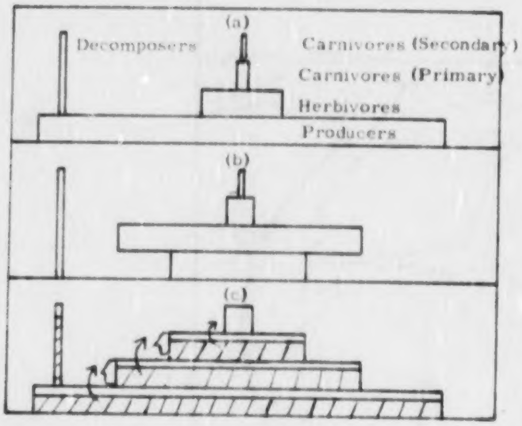

Figure 5. HYPOTHETICAL PYRAMIDS of (a) Numbers of individuals, (b) Biomass, and (c) Energy (Shading Indicates Energy Loss).

V BIOTIC COMMUNITIES

A Plankton are the macroscopic and microscopic animals, plants, bacteria, etc., floating free in the open water. Many clog filters, cause tastes, odors, and other troubles in water supplies. Eggs and larvae of larger forms are often present.

1 Phytoplankton are plant-like. These are the dominant producers of the waters, fresh and salt, "the grass of the seas".

2 Zooplankton are animal-like. Includes many different animal types, range in size from minute protozoa to gigantic marine jellyfishes.

B Periphyton (or Aufwuchs) - The communities of microscopic organisms associated with submerged surfaces of any type or depth. Includes bacteria, algae, protozoa, and other microscopic animals, and often the young or embryonic stages of algae and other organisms that normally grow up to become a part of the benthos (see below). Many planktonic types will also adhere to surfaces as periphyton, and some typical periphyton may break off and be collected as plankters.

C Benthos are the plants and animals living on, in, or closely associated with the bottom. They include plants and invertebrates.

D Nekton are the community of strong aggressive swimmers of the open waters, often called pellagic. Certain fishes, whales, and invertebrates such as shrimps and squids are included here.

E The marsh community is based on larger "higher" plants, floating and emergent. Both marine and freshwater marshes are areas of enormous biological production. Collectively known as "wetlands", they bridge the gap between the waters and the dry lands.

VI PRODUCTIVITY

A The biological resultant of all physical and chemical factors in the quantity of life that may actually be present. The ability to produce this "biomass" is often referred to as the "productivity" of a body of water. This is neither good nor bad per se. A water of low productivity is a "poor" water biologically, and also a relatively "pure" or "clean" water; hence desirable as a water supply or a bathing beach. A productive water on the other hand may be a nuisance to man or highly desirable. It is a nuisance if foul odors and/or weed-chocked waterways result, it is desirable if bumper crops of bass, catfish, or oysters are produced. Open oceans have a low level of productivity in general.

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This outline was prepared by H. W. Jackson, Chief Biologist, National Training Center, Water Programs Operations, EPA, Cincinnati, OH 45268.

Descriptors:
Aquatic Environment, Estuarine Environment, Lentic Environment, Lotic Environment, Currents, Marshes, Limnology, Water Properties

THE AQUATIC ENVIRONMENT

Part 3. The Freshwater Environment

I INTRODUCTION

The freshwater environment as considered herein refers to those inland waters not detectably diluted by ocean waters, although the lower portions of rivers are subject to certain tidal flow effects.

Certain atypical inland waters such as saline or alkaline lakes, springs, etc., are not treated, as the main objective here in typical inland water.

All waters have certain basic biological cycles and types of interactions most of which have already been presented, hence this outline will concentrate on aspects essentially peculiar to fresh inland waters.

II PRESENT WATER QUALITY AS A FUNCTION OF THE EVOLUTION OF FRESH WATERS

A The history of a body of water determines its present condition. Natural waters have evolved in the course of geologic time into what we know today.

B Streams

In the course of their evolution, streams in general pass through four stages of development which may be called: birth, youth, maturity, and old age.

These terms or conditions may be employed or considered in two contexts: temporal, or spatial. In terms of geologic time, a given point in a stream may pass through each of the stages described below or: at any given time, these various stages of development can be loosely identified in successive reaches of a stream traveling from its headwaters to base level in ocean or major lake.

1 Establishment or birth. This might be a "dry run" or headwater stream-bed, before it had eroded down to the level of ground water.

During periods of run-off after a rain or snow-melt, such a gulley would have a flow of water which might range from torrential to a mere trickle. Erosion may proceed rapidly as there is no permanent aquatic flora or fauna to stabilize streambed materials. On the other hand, terrestrial grass or forest growth may retard erosion. When the run-off has passed, however, the "streambed" is dry.

2 Youthful streams. When the streambed is eroded below the ground water level, spring or seepage water enters, and the stream becomes permanent. An aquatic flora and fauna develops and water flows the year round. Youthful streams typically have a relatively steep gradient, rocky beds, with rapids, falls, and small pools.

3 Mature streams. Mature streams have wide valleys, a developed flood plain, are deeper, more turbid, and usually have warmer water, sand, mud, silt, or clay bottom materials which shift with increase in flow. In their more favorable reaches, streams in this condition are at a peak of biological productivity. Gradients are moderate, riffles or rapids are often separated by long pools.

4 In old age, streams have approached geologic base level, usually the ocean. During flood stage they scour their beds and deposit materials on the flood plain which may be very broad and flat. During normal flow the channel is refilled and many shifting bars are developed.

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(Under the influence of man this pattern may be broken up, or temporarily interrupted. Thus an essentially "youthful" stream might take on some of the characteristics of a "mature" stream following soil erosion, organic enrichment, and increased surface runoff. Correction of these conditions might likewise be followed by at least a partial reversion to the "original" condition).

C Lakes and Reservoirs

Geological factors which significantly affect the nature of either a stream or lake include the following:

1 The geographical location of the drainage basin or watershed.

2 The size and shape of the drainage basin.

3 The general topography, i.e., mountainous or plains.

4 The character of the bedrocks and soils.

5 The character, amount, annual distribution, and rate of precipitation.

6 The natural vegetative cover of the land is, of course, responsive to and responsible for many of the above factors and is also severely subject to the whims of civilization. This is one of the major factors determining run-off versus soil absorption, etc.

D Lakes have a developmental history which somewhat parallels that of streams. This process is often referred to as natural eutrophication.

1 The methods of formation vary greatly, but all influence the character and subsequent history of the lake.

In glaciated areas, for example, a huge block of ice may have been covered with till. The glacier retreated, the ice melted, and the resulting hole became a lake. Or, the glacier may actually scoop out a hole. Landslides may dam valleys, extinct volcanoes may collapse, etc., etc.

2 Maturing or natural eutrophication of lakes.

a If not already present shoal areas are developed through erosion and deposition of the shore material by wave action and undertow.

b Currents produce bars across bays and thus cut off irregular areas.

c Silt brought in by tributary streams settles out in the quiet lake water

d Algae grow attached to surfaces, and floating free as plankton. Dead organic matter begins to accumulate on the bottom.

e Rooted aquatic plants grow on shoals and bars, and in doing so cut off bays and contribute to the filling of the lake.

f Dissolved carbonates and other materials are precipitated in the deeper portions of the lake in part through the action of plants.

g When filling is well advanced, mats of sphagnum moss may extend outward from the shore. These mats are followed by sedges and grasses which finally convert the lake into a marsh.

3 Extinction of lakes. After lakes reach maturity, their progress toward filling up is accelerated. They become extinct through:

a The downcutting of the outlet.

b Filling with detritus eroded from the shores or brought in by tributary streams.

c Filling by the accumulation of the remains of vegetable materials growing in the lake itself. (Often two or three processes may act concurrently)

III PRODUCTIVITY IN FRESH WATERS

A Fresh waters in general and under natural conditions by definition have a lesser supply of dissolved substances than marine waters, and thus a lesser basic potential for the growth of aquatic organisms. By the same token, they may be said to be more sensitive to the addition of extraneous materials (pollutants, nutrients, etc.) The following notes are directed toward natural geological and other environmental factors as they affect the productivity of fresh waters.

B Factors Affecting Stream Productivity (See Table 1)

TABLE 1

EFFECT OF SUBSTRATE ON STREAM PRODUCTIVITY*

(The productivity of sand bottoms is taken as 1)

Bottom Material	Relative Productivity
Sand	1
Marl	6
Fine Gravel	9
Gravel and silt	14
Coarse gravel	32
Moss on fine gravel	89
Fissidens (moss) on coarse gravel	111
Ranunculus (water buttercup)	194
Watercress	301
Anacharis (waterweed)	452

*Selected from Tarzwell 1937

To be productive of aquatic life, a stream must provide adequate nutrients, light, a suitable temperature, and time for growth to take place.

1 Youthful streams, especially on rock or sand substrates are low in essential nutrients. Temperatures in mountainous regions are usually low, and due to the steep gradient, time for growth is short. Although ample light is available, growth of true plankton is thus greatly limited.

2 As the stream flows toward a more "mature" condition, nutrients tend to accumulate, and gradient diminishes and so time of flow increases, temperature tends to increase, and plankton flourish.

Should a heavy load of inert silt develop on the other hand, the turbidity would reduce the light penetration and consequently the general plankton production would diminish.

3 As the stream approaches base level (old age) and the time available for plankton growth increases, the balance between turbidity, nutrient levels, and temperature and other seasonal conditions, determines the overall productivity.

C Factors Affecting the Productivity of lakes (See Table 2)

1 The size, shape, and depth of the lake basin. Shallow water is more productive than deeper water since more light will reach the bottom to stimulate rooted plant growth. As a corollary, lakes with more shoreline, having more shallow water, are in general more productive. Broad shallow lakes and reservoirs have the greatest production potential (and hence should be avoided for water supplies).

TABLE 2

EFFECT OF SUBSTRATE ON LAKE PRODUCTIVITY *

(The productivity of sand bottoms is taken as 1)

Bottom Material	Relative Productivity
Sand	1
Pebbles	4
Clay	8
Flat rubble	9
Block rubble	11
Shelving rock	77

* Selected from Tarzwell 1937

2 Hard waters are generally more productive than soft waters as there are more plant nutrient minerals available. This is often greatly influenced by the character of the soil and rocks in the watershed and the quality and quantity of ground water entering the lake. In general, pH ranges of 6.8 to 8.2 appear to be most productive.

3 Turbidity reduces productivity as light penetration is reduced.

4 The presence or absence of thermal stratification with its semi-annual turnovers affects productivity by distributing nutrients throughout the water mass.

5 Climate, temperature, prevalence of ice and snow, are also of course important.

D Factors Affecting the Productivity of Reservoirs

1 The productivity of reservoirs is governed by much the same principles as that of lakes, with the difference that the water level is much more under the control of man. Fluctuations in water level can be used to deliberately increase or decrease productivity. This can be demonstrated by a comparison of the TVA reservoirs which practice a summer drawdown with some of those in the west where a winter drawdown is the rule.

2 The level at which water is removed from a reservoir is important to the productivity of the stream below. The hypolimnion may be anaerobic while the epilimnion is aerobic, for example, or the epilimnion is poor in nutrients while the hypolimnion is relatively rich.

3 Reservoir discharges also profoundly affect the DO, temperature, and turbidity in the stream below a dam. Too much fluctuation in flow may permit sections of the stream to dry, or provide inadequate dilution for toxic waste.

IV CULTURAL EUTROPHICATION

A The general processes of natural eutrophication, or natural enrichment and productivity have been briefly outlined above.

B When the activities of man speed up these enrichment processes by introducing unnatural quantities of nutrients (sewage, etc.) the result is often called cultural eutrophication. This term is often extended beyond its original usage to include the enrichment (pollution) of streams, estuaries, and even oceans, as well as lakes.

V CLASSIFICATION OF LAKES AND RESERVOIRS

A The productivity of lakes and impoundments is such a conspicuous feature that it is often used as a convenient means of classification.

1 Oligotrophic lakes are the younger, less productive lakes, which are deep, have clear water, and usually support Salmonoid fishes in their deeper waters.

2 Eutrophic lakes are more mature, more turbid, and richer. They are usually shallower. They are richer in dissolved solids; N, P, and Ca are abundant. Plankton is abundant and there is often a rich bottom fauna.

3 Dystrophic lakes, such as bog lakes, are low in Ph, water yellow to brown, dissolved solids, N, P, and Ca scanty but humic materials abundant, bottom fauna and plankton poor, and fish species are limited.

B Reservoirs may also be classified as storage, and run of the river.

1 Storage reservoirs have a large volume in relation to their inflow.

2 Run of the river reservoirs have a large flow-through in relation to their storage value.

C According to location, lakes and reservoirs may be classified as polar, temperate, or tropical. Differences in climatic and geographic conditions result in differences in their biology.

VI SUMMARY

A A body of water such as a lake, stream, or estuary represents an intricately balanced system in a state of dynamic equilibrium. Modification imposed at one point in the system automatically results in compensatory adjustments at associated points.

B The more thorough our knowledge of the entire system, the better we can judge where to impose control measures to achieve a desired result.

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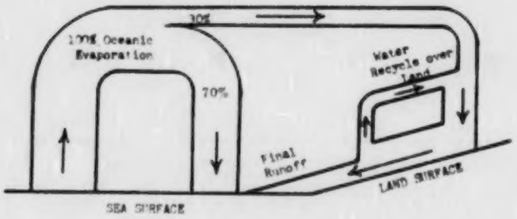

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C For this presentation, the marine environment will be (1) described using an ecological approach, (2) characterized ecologically by comparing it with freshwater and estuarine environments, and (3) considered as a functional ecological system (ecosystem).

II FRESHWATER, ESTUARINE, AND MARINE ENVIRONMENTS

Distinct differences are found in physical, chemical, and biotic factors in going from a freshwater to an oceanic environment. In general, environmental factors are more constant in freshwater (rivers) and oceanic environments than in the highly variable and harsh environments of estuarine and coastal waters. (Figure 2)

A Physical and Chemical Factors

Rivers, estuaries, and oceans are compared in Figure 2 with reference to the relative instability (or variation) of several important parameters. In the oceans, it will be noted, very little change occurs in any parameter. In rivers, while "salinity" (usually referred to as "dissolved solids") and temperature (accepting normal seasonal variations) change little, the other four parameters vary considerably. In estuaries, they all change.

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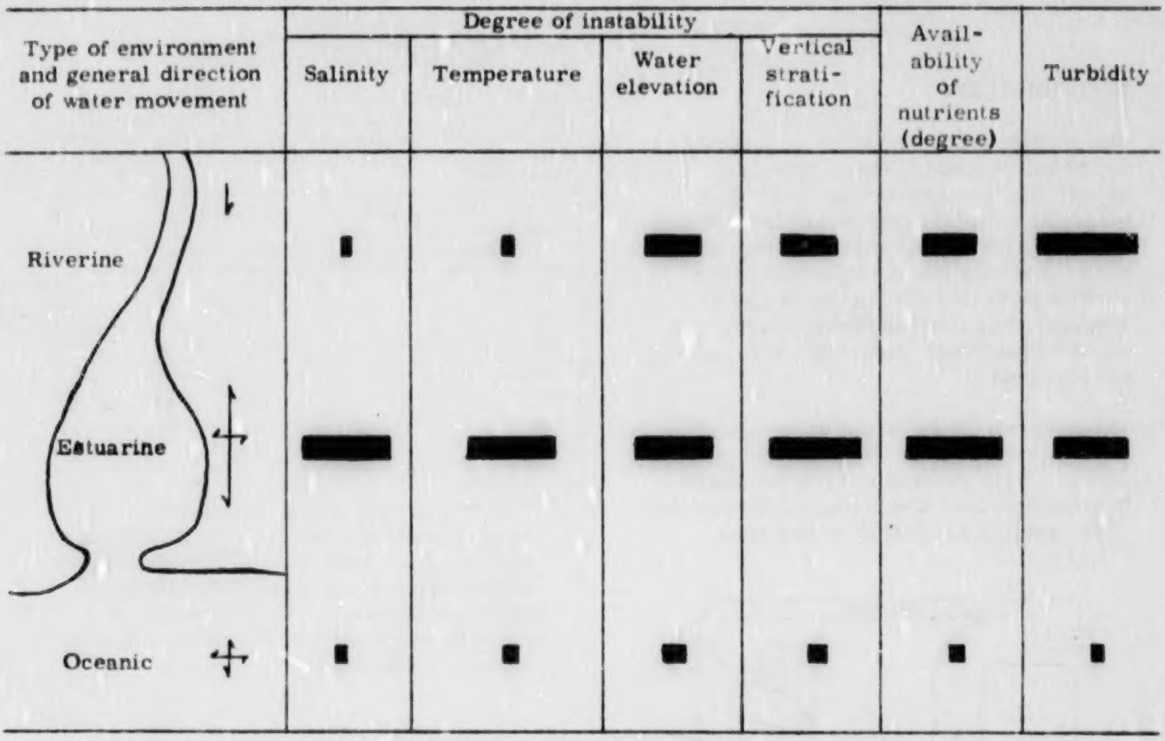

Figure 2. RELATIVE VALUES OF VARIOUS PHYSICAL AND CHEMICAL FACTORS FOR RIVER, ESTUARINE, AND OCEANIC ENVIRONMENTS

B Biotic Factors

1 A complex of physical and chemical factors determine the biotic composition of an environment. In general, the number of species in a rigorous, highly variable environment tends to be less than the number in a more stable environment (Hedgpeth, 1966).

2 The dominant animal species (in terms of total biomass) which occur in estuaries are often transient, spending only a part of their lives in the estuaries. This results in better utilization of a rich environment.

C Zones of the Sea

The nearshore environment is often classified in relation to tide level and water depth. The nearshore and offshore oceanic regions together, are often classified with reference to light penetration and water depth. (Figure 3)

1 Neritic - Relatively shallow-water zone which extends from the high-tide mark to the edge of the continental shelf.

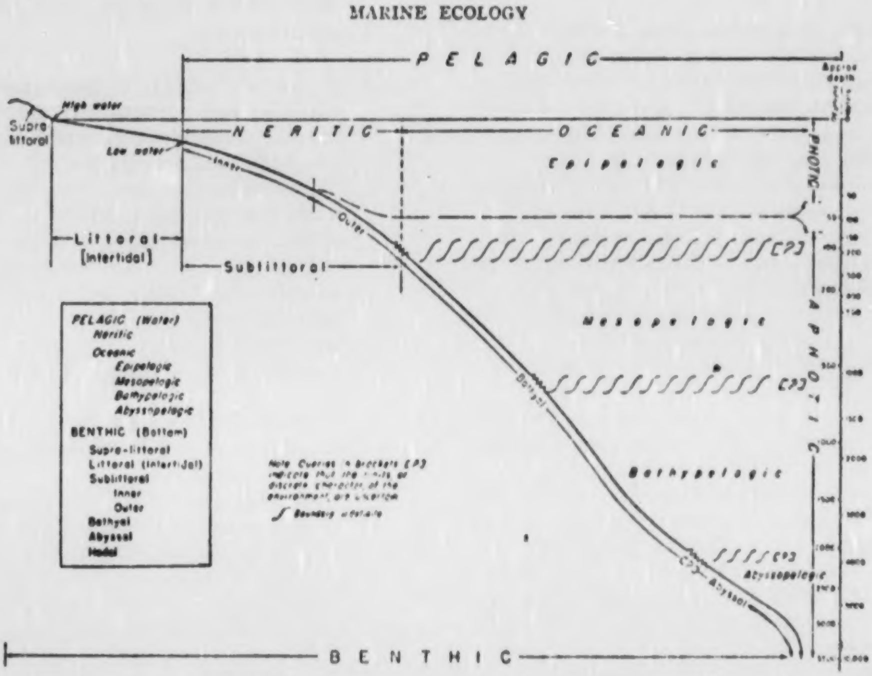

FIGURE 3—*Classification of marine environments*

a Stability of physical factors is intermediate between estuarine and oceanic environments.

b Phytoplankters are the dominant producers but in some locations attached algae are also important as producers.

c The animal consumers are zooplankton, nekton, and benthic forms.

2 Oceanic - The region of the ocean beyond the continental shelf. Divided into three parts, all relatively poorly populated compared to the neritic zone.

a Euphotic zone - Waters into which sunlight penetrates (often to the bottom in the neritic zone). The zone of primary productivity often extends to 600 feet below the surface.

1) Physical factors fluctuate less than in the neritic zone.

2) Producers are the phytoplankton and consumers are the zooplankton and nekton.

b Bathyal zone - From the bottom of the euphotic zone to about 2000 meters.

1) Physical factors relatively constant but light is absent.

2) Producers are absent and consumers are scarce.

c Abyssal zone - All the sea below the bathyal zone.

1) Physical factors more constant than in bathyal zone.

2) Producers absent and consumers even less abundant than in the bathyal zone.

III SEA WATER AND THE BODY FLUIDS

A Sea water is a remarkably suitable environment for living cells, as it contains all of the chemical elements essential to the growth and maintenance of plants and animals. The ratio and often the concentration of the major salts of sea water are strikingly similar in the cytoplasm and body fluids of marine organisms. This similarity is also evident, although modified somewhat in the body fluids of fresh water and terrestrial animals. For example, sterile sea water may be used in emergencies as a substitute for blood plasma in man.

B Since marine organisms have an internal salt content similar to that of their surrounding medium (isotonic condition) osmoregulation poses no problem. On the other hand, fresh water organisms are hypertonic (osmotic pressure of body fluids is higher than that of the surrounding water). Hence, fresh water animals must constantly expend more energy to keep water out (i.e., high osmotic pressure fluids contain more salts, the action being then to dilute this concentration with more water).

1 Generally, marine invertebrates are narrowly poikilosmotic, i.e., the salt concentration of the body fluids changes with that of the external medium. This has special significance in estuarine situations where salt concentrations of the water often vary considerably in short periods of time.

2 Marine bony fish (teleosts) have lower salt content internally than the external environment (hypotonic). In order to prevent dehydration, water is ingested and salts are excreted through special cells in the gills.

IV FACTORS AFFECTING THE DISTRIBUTION OF MARINE AND ESTUARINE ORGANISMS

A Salinity. Salinity is the single most constant and controlling factor in the marine environment, probably followed by temperature. It ranges around 35,000 mg. per liter, or "35 parts per thousand" (symbol: 35‰) in the language of the oceanographer. While variations in the open ocean are relatively small, salinity decreases rapidly as one approaches shore and proceeds through the estuary and up into fresh water with a salinity of "0 ‰ (see Figure 2)

B Salinity and temperature as limiting factors in ecological distribution.

1 Organisms differ in the salinities and temperatures in which they prefer to live, and in the variabilities of these parameters which they can tolerate. These preferences and tolerances often change with successive life history stages, and in turn often dictate where the organisms live: their "distribution."

2 These requirements or preferences often lead to extensive migrations of various species for breeding, feeding, and growing stages. One very important result of this is that an estuarine environment is an absolute necessity for over half of all coastal commercial and sport related species of fishes and invertebrates, for either all or certain portions of their life histories. (Part V, figure 8)

3 The Greek word roots "eury" (meaning wide) and "steno" (meaning narrow) are customarily combined with such words as "haline" for salt, and "thermal" for temperature, to give us "euryhaline" as an adjective to characterize an organism able to tolerate a wide range of salinity, for example; or "stenothermal" meaning one which cannot stand much change in temperature. "Meso-" is a prefix indicating an intermediate capacity.

C Marine, estuarine, and fresh water organisms. (See Figure 4)

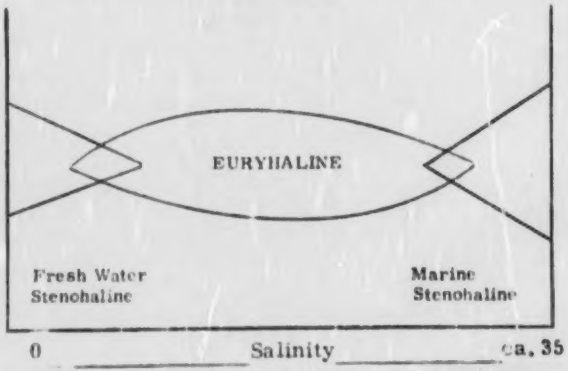

Figure 4. Salinity Tolerance of Organisms

1 Offshore marine organisms are, in general, both stenohaline and stenothermal unless, as noted above, they have certain life history requirements for estuarine conditions.

2 Fresh water organisms are also stenohaline, and (except for seasonal adaptation) meso- or stenothermal. (Figure 2)

3 Indigenous or native estuarine species that normally spend their entire lives in the estuary are relatively few in number. (See Figure 5). They are generally meso- or euryhaline and meso- or eurythermal.

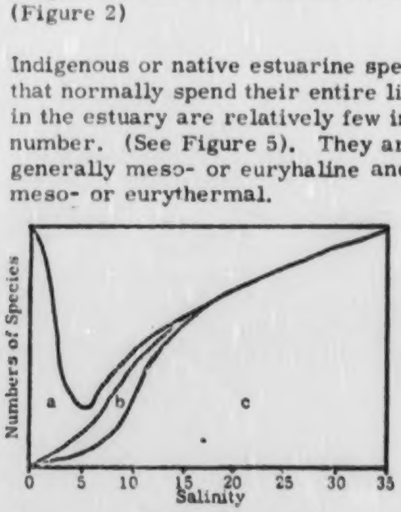

Figure 5. DISTRIBUTION OF ORGANISMS IN AN ESTUARY

a Euryhaline, freshwater
b Indigenous, estuarine, (mesohaline)
c Euryhaline, marine

4 Some well known and interesting examples of migratory species which change their environmental preferences with the life history stage include the shrimp (mentioned above), striped bass, many herrings and relatives, the salmons, and many others. None are more dramatic than the salmon hordes which lay their eggs in freshwater streams, migrate far out to sea to feed and grow, then return to the stream where they hatched to lay their own eggs before dying.

5 Among euryhaline animals landlocked (trapped), populations living in lowered salinities often have a smaller maximum size than individuals of the same species living in more saline waters. For example, the lamprey (Petromyzon marinus) attains a length of 30 - 36" in the sea, while in the Great Lakes the length is 18 - 24".

Usually the larvae of aquatic organisms are more sensitive to changes in salinity than are the adults. This characteristic both limits and dictates the distribution and size of populations.

D The effects of tides on organisms.

1 Tidal fluctuations probably subject the benthic or intertidal populations to the most extreme and rapid variations of environmental stress encountered in any aquatic habitat. Highly specialized communities have developed in this zone, some adapted to the rocky surf zones of the open coast, others to the muddy inlets of protected estuaries. Tidal reaches of fresh water rivers, sandy beaches, coral reefs and mangrove swamps in the tropics; all have their own floras and faunas. All must emerge and flourish when whatever water there is rises and covers or tears at them, all must collapse or retract to endure drying, blazing tropical sun, or freezing arctic ice during the low tide interval. Such a community is depicted in Figure 6.

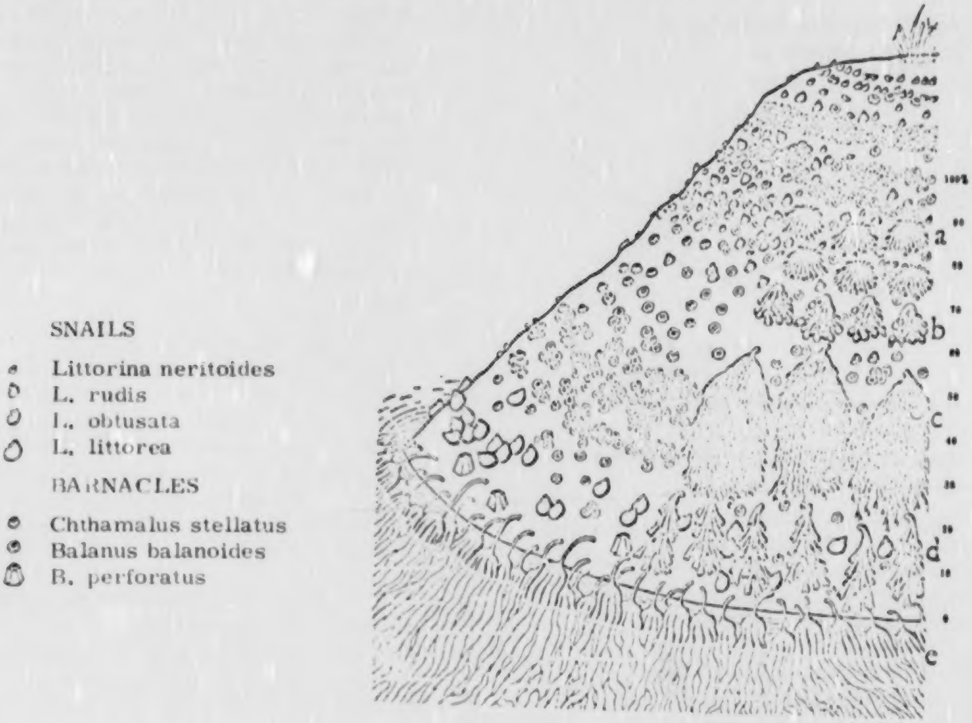

Figure 6

Zonation of plants, snails, and barnacles on a rocky shore. While this diagram is based on the situation on the southwest coast of England, the general idea of zonation may be applied to any temperate rocky ocean shore, though the species will differ. The gray zone consists largely of lichens. At the left is the zonation of rocks with exposure too extreme to support algae; at the right, on a less exposed situation, the animals are mostly obscured by the algae. Figures at the right hand margin refer to the percent of time that the zone is exposed to the air, i.e., the time that the tide is out. Three major zones can be recognized: the Littorina zone (above the gray zone); the Balanoid zone (between the gray zone and the laminarias); and the Laminaria zone. a. Pelvetia canaliculata; b. Fucus spiralis; c. Ascophyllum nodosum; d. Fucus serratus; e. Laminaria digitata. (Based on Stephenson)

V FACTORS AFFECTING THE PRODUCTIVITY OF THE MARINE ENVIRONMENT

A The sea is in continuous circulation. Without circulation, nutrients of the ocean would eventually become a part of the bottom and biological production would cease. Generally, in all oceans there exists a warm surface layer which overlies the colder water and forms a two-layer system of persistent stability. Nutrient concentration is usually greatest in the lower zone. Wherever a mixing or disturbance of these two layers occurs biological production is greatest.

B The estuaries are also a mixing zone of enormous importance. Here the fertility washed off the land is mingled with the nutrient capacity of seawater, and many of the would's most productive waters result.

C When man adds his cultural contributions of sewage, fertilizer, silt or toxic waste, it is no wonder that the dynamic equilibrium of the ages is rudely upset, and the environmentalist cries, "See what man hath wrought"!

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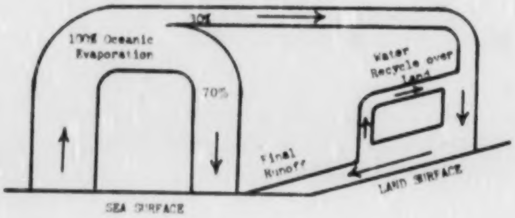

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Rivers, estuaries, and oceans are compared in Figure 2 with reference to the relative instability (or variation) of several important parameters. In the oceans, it will be noted, very little change occurs in any parameter. In rivers, while "salinity" (usually referred to as "dissolved solids") and temperature (accepting normal seasonal variations) change little, the other four parameters vary considerably. In estuaries, they all change.

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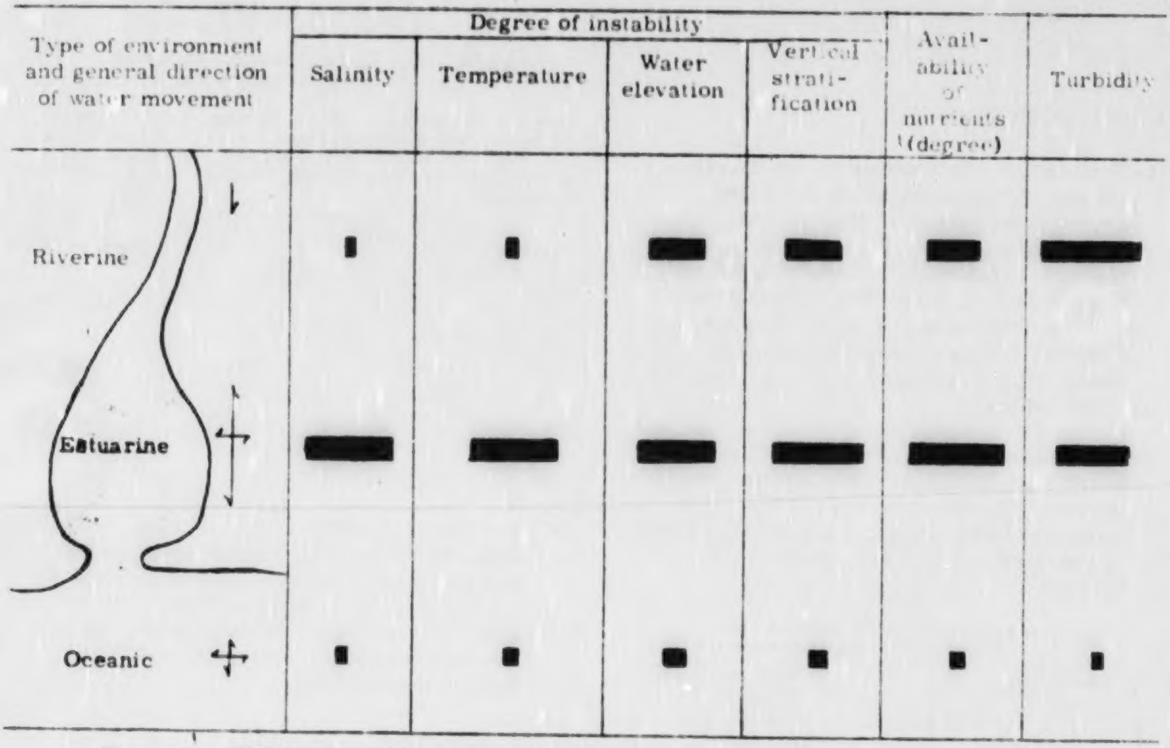


Figure 2. RELATIVE VALUES OF VARIOUS PHYSICAL AND CHEMICAL FACTORS FOR RIVER, ESTUARINE, AND OCEANIC ENVIRONMENTS

B Biotic Factors

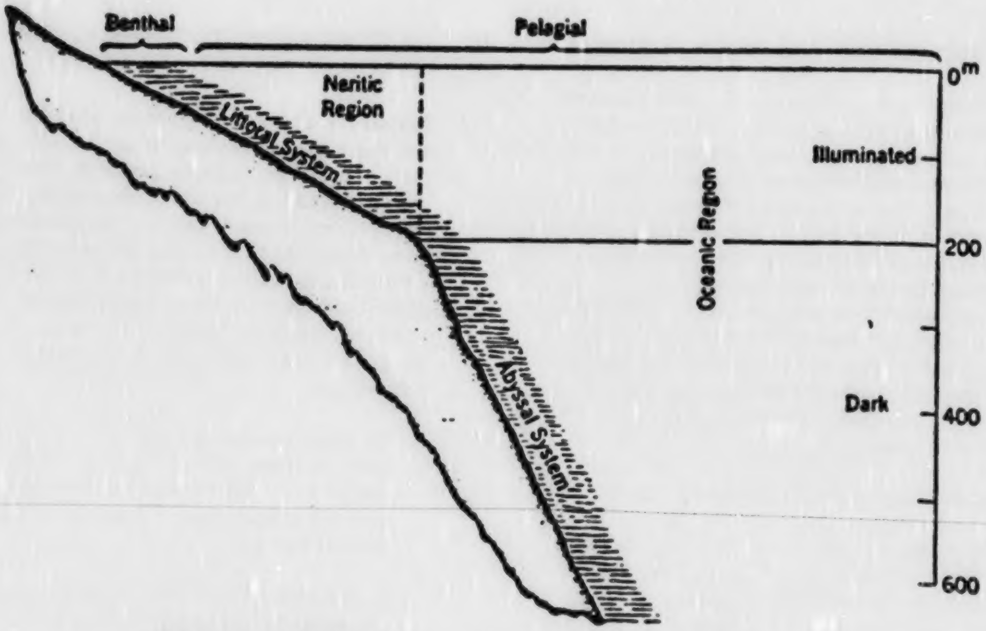
1 A complex of physical and chemical factors determine the biotic composition of an environment. In general, the number of species in a highly variable environment tends to be less than the number in a more stable environment (Hedgpeth, 1966).

2 The dominant animal species (in terms of total biomass) which occur in estuaries are often transient, spending only a part of their lives in the estuaries. This results in better utilization of a rich environment.

C Zones of the Sea

The nearshore environment is often classified in relation to tide level and water depth. The nearshore and oceanic regions together are often classified in relation to light penetration and water depth.

1 Neritic - Relatively shallow-water zone which extends from the high-tide mark to the edge of the continental shelf. (Figure 3)



Primary subdivisions of the marine habitat.

Figure 3.

a Stability of physical factors is intermediate between estuarine and oceanic environments.

b Phytoplankters are the dominant producers but in some locations attached algae are also important as producers.

c The animal consumers are zooplankton, nekton, and benthic forms.

2 Oceanic - The region of the ocean beyond the continental shelf. Divided into three parts, all relatively poorly populated compared to the neritic zone.

a Euphotic zone - Waters into which sunlight penetrates (often to the bottom in the neritic zone). The zone of basic productivity. Often extends to 600 feet below the surface.

1) Physical factors fluctuate less than in the neritic zone.

2) Producers are the phytoplankton and consumers are the zooplankton and nekton.

b Bathyal zone - From the bottom of the euphotic zone to about 6,000 feet.

1) Physical factors relatively constant but light is absent.

2) Producers are absent and consumers are scarce.

c Abyssal zone - All the sea below the bathyal zone.

1) Physical factors more constant than in bathyal zone.

2) Producers absent and consumers not as abundant as in the bathyal zone.

III SEA WATER AND THE BODY FLUIDS

A Sea water is a most suitable environment for living cells, because it contains all of the chemical elements essential to the growth and maintenance of plants and animals. The ratio and often the concentration of the major salts of sea water are strikingly similar in the cytoplasma and body fluids of marine organisms. This similarity is also evident, although modified somewhat in the body fluids of both fresh water and terrestrial animals. For example, sea water may be used in emergencies as a substitute for blood plasma in man.

B Since marine organisms have an internal salt content similar to that of their surrounding medium (isotonic condition) osmoregulation poses no problem. On the other hand, fresh water organisms are hypertonic (osmotic pressure of body fluids is higher than that of the surrounding water). Hence, fresh water animals must constantly expend more energy to keep water out (i.e., high osmotic pressure fluids contain more salts, the action being then to dilute this concentration with more water).

1 Generally, marine invertebrates are narrowly poikilosmotic, i.e., the salt concentration of the body fluids changes with that of the external medium. This has special significance in estuarine situations where salt concentrations of the water often vary considerably in short periods of time.

2 Marine bony fish (teleosts) have lower salt content internally than externally (hypotonic). In order to prevent dehydration, water is ingested and salts are excreted through special cells in the gills.

IV FACTORS AFFECTING THE DISTRIBUTION OF MARINE ORGANISMS

A **Salinity** - The concentration of salts is not the same everywhere in the sea; in the open ocean salinity is much less variable than in the ever changing estuary or coastal water. Organisms have different tolerances to salinity which limit their distribution. The distributions may be in large water masses, such as the Gulf Stream, Sargasso Sea, etc., or in bays and estuaries.

1 In general, animals in the estuarine environment are able to withstand large and rapid changes in salinity and temperature. These animals are classified as:

a Euryhaline ("eury" meaning wide) - wide tolerance to salinity changes.

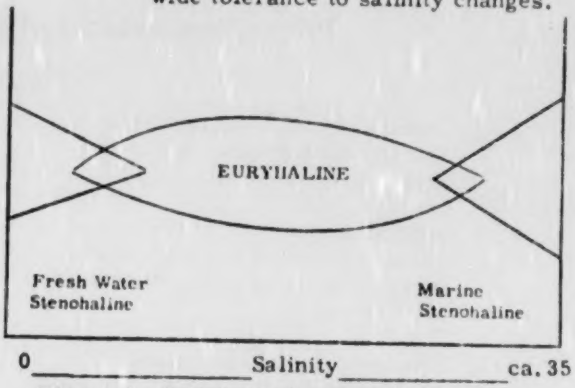


Figure 4. Salinity Tolerance of Organisms

b Eurythermal - wide tolerance to temperature changes.

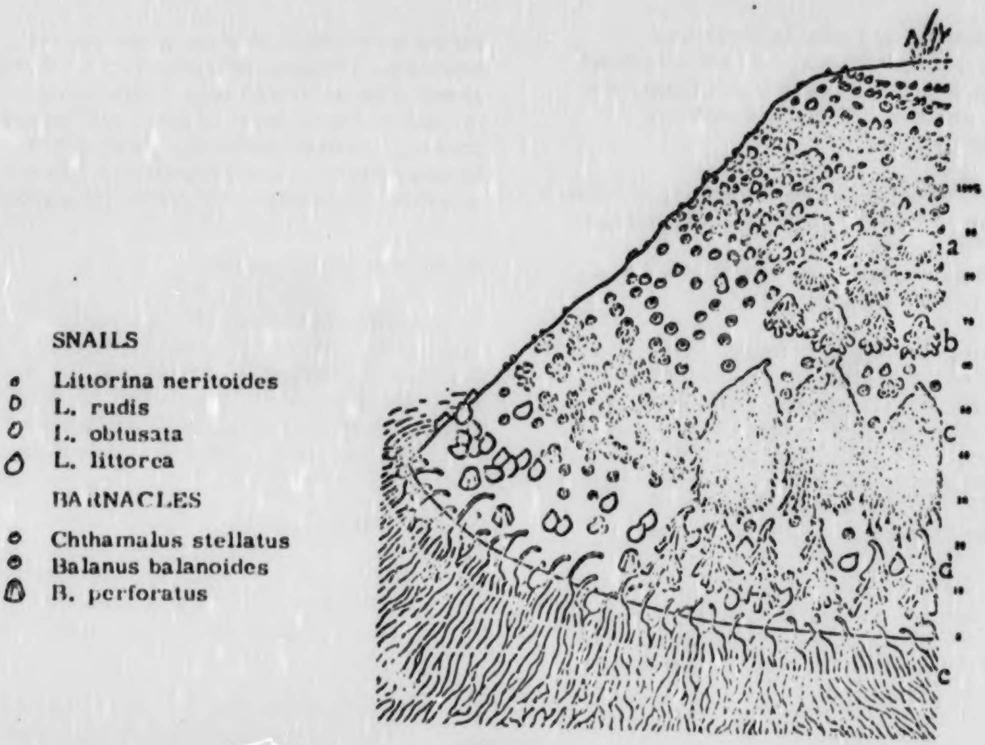


Figure 5

Zonation of plants, snails, and barnacles on a rocky shore. While this diagram is based on the situation on the southwest coast of England, the general idea of zonation may be applied to any temperate rocky ocean shore, though the species will differ. The gray zone consists largely of lichens. At the left is the zonation of rocks with exposure too extreme to support algae; at the right, on a less exposed situation, the animals are mostly obscured by the algae. Figures at the right hand margin refer to the percent of time that the zone is exposed to the air, i.e., the time that the tide is out. Three major zones can be recognized: the Littorina zone (above the gray zone); the Balanoid zone (between the gray zone and the laminarias); and the Laminaria zone. a. Pelvetia canaliculata; b. Fucus spiralis; c. Ascophyllum nodosum; d. Fucus serratus; e. Laminaria digitata. (Based on Stephenson)

2 In general, animals in river and oceanic environments cannot withstand large and rapid changes in salinity and temperature. These animals are classified as:

a Stenohaline ("steno" meaning narrow) - narrow tolerance to salinity changes.

b Stenothernal - narrow tolerance to temperature changes.

3 Among euryhaline animals, those living in lowered salinities often have a smaller maximum size than those of the same species living in more saline waters. For example, the lamprey (Petromyzon marinus) attains a length of 30 - 36" in the sea, while in the Great Lakes the length is 18 - 24".

4 Usually the larvae of marine organisms are more sensitive to changes in salinity than are the adults. This characteristic limits both the distribution and size of populations.

B Tides

Tidal fluctuation is a phenomenon unique to the seas (with minor exceptions). It is a twice daily rise and fall in the sea level caused by the complicated interaction of many factors including sun, moon, and the daily rotation of the earth. Tidal heights vary from day to day and place to place, and are often accentuated by local meteorological conditions. The rise and fall may range from a few inches or less to fifty feet or more.

V FACTORS AFFECTING THE PRODUCTIVITY OF THE MARINE ENVIRONMENT

The sea is in continuous circulation. Without circulation, nutrients of the ocean would eventually become a part of the bottom and biomass production would cease. Generally, in all oceans there exists a warm surface layer which overlies the colder water and forms a two-layer system of persistent stability. Nutrient concentration is usually greatest in the lower zone. Wherever a mixing or disturbance of these two layers occurs, biomass production is greatest. Factors causing this breakup are, therefore, of utmost importance concerning productivity.

ACKNOWLEDGEMENT:

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THE AQUATIC ENVIRONMENT

Part 5: Wetlands

I INTRODUCTION

A Broadly defined, wetlands are areas which are "to wet to plough but too thick to flow." The soil tends to be saturated with water, salt or fresh, and numerous channels or ponds of shallow or open water are common. Due to ecological features too numerous and variable to list here, they comprise in general a rigorous (highly stressed) habitat, occupied by a small relatively specialized indigenous (native) flora and fauna.

B They are prodigiously productive however, and many constitute an absolutely essential habitat for some portion of the life history of animal forms generally recognized as residents of other habitats (Figure 8). This is particularly true of tidal marshes as mentioned below.

C Wetlands in toto comprise a remarkably large proportion of the earth's surface, and the total organic carbon bound in their mass constitutes an enormous sink of energy.

D Since our main concern here is with the "aquatic" environment, primary emphasis will be directed toward a description of wetlands as the transitional zone between the waters and the land, and how their desecration by human culture spreads degradation in both directions.

II TIDAL MARSHES AND THE ESTUARY

A "There is no other case in nature, save in the coral reefs, where the adjustment of organic relations to physical condition is seen in such a beautiful way as the balance between the growing marshes and the tidal streams by which they are at once nourished and worn away." (Shaler, 1886)

B Estuarine pollution studies are usually devoted to the dynamics of the circulating water, its chemical, physical, and biological parameters, bottom deposits, etc.

C It is easy to overlook the intimate relationships which exist between the bordering marshland, the moving waters, the tidal flats, subtidal deposition, and seston whether of local, oceanic, or riverine origin.

D The tidal marsh (some inland areas also have salt marshes) is generally considered to be the marginal areas of estuaries and coasts in the intertidal zone, which are dominated by emergent vegetation. They generally extend inland to the farthest point reached by the spring tides, where they merge into freshwater swamps and marshes (Figure 1). They may range in width from nonexistent on rocky coasts to many kilometers.

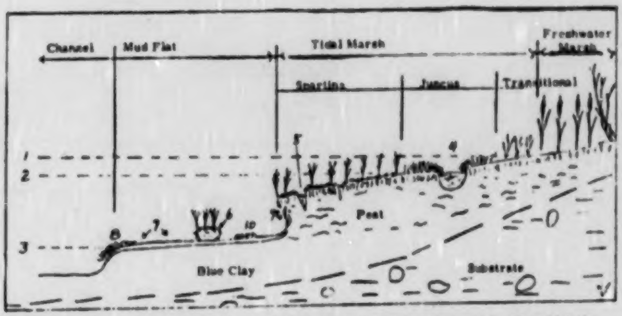


Figure 1. Zonation in a positive New England estuary. 1. Spring tide level, 2. Mean high tide, 3. Mean low tide, 4. Hog hole, 5. Ice cleavage pool, 6. Chunk of Spartina turf deposited by ice, 7. Organic ooze with associated community, 8. eelgrass (Zostera), 9. Ribbed mussels (modiolus)-clam (mya) - mud snail (Nassa) community. 10. Sea lettuce (Ulva)

III MARSH ORIGINS AND STRUCTURES

A In general, marsh substrates are high in organic content, relatively low in minerals and trace elements. The upper layers bound together with living roots called turf, underlaid by more compacted peat type material.

1 Rising or eroding coastlines may expose peat from ancient marsh growth to wave action which cuts into the soft peat rapidly (Figure 2).

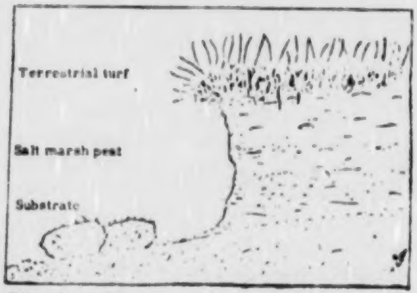


Figure 2 Diagrammatic section of eroding peat cliff

Such banks are likely to be cliff-like, and are often undercut. Chunks of peat are often found lying about on harder substrate below high tide line. If face of cliff is well above high water, overlying vegetation is likely to be typically terrestrial of the area. Marsh type vegetation is probably absent.

2 Low lying deltaic, or sinking coastlines, or those with low energy wave action are likely to have active marsh formation in progress. Sand dunes are also common in such areas (Figure 3). General coastal configuration is a factor.

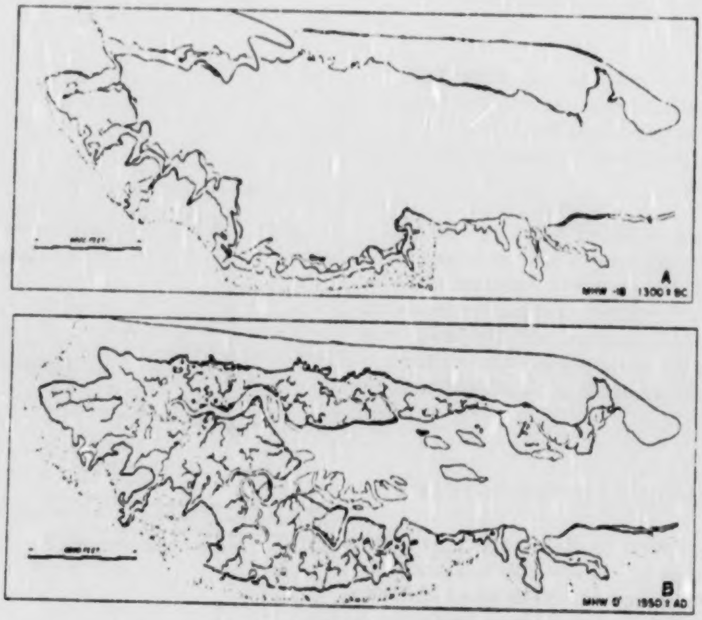


Figure 3

Development of a Massachusetts Marsh since 1300 BC, involving an 18 foot rise in water level. Shaded area indicates sand dunes. Note meandering marsh tidal drainage. A: 1300 BC, B: 1950 AD.

a Rugged or precipitous coasts or slowly rising coasts, typically exhibit narrow shelves, sea cliffs, fjords, massive beaches, and relatively less marsh area (Figure 4). An Alaskan fjord subject to recent catastrophic subsidence and rapid deposition of glacial flour shows evidence of the recent encroachment of saline waters in the presence of recently buried trees and other terrestrial vegetation, exposure of layers of salt marsh peat along the edges of channels, and a poorly compacted young marsh turf developing at the new high water level (Figure 5).

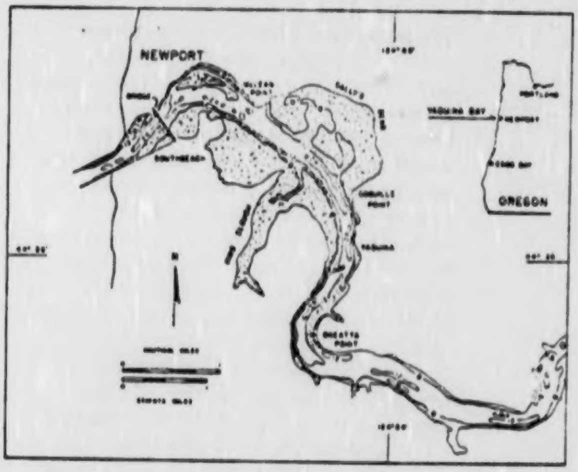


Figure 4 A River Mouth on a Slowly Rising Coast. Note absence of deltaic development and relatively little marshland, although mud flats stippled are extensive.

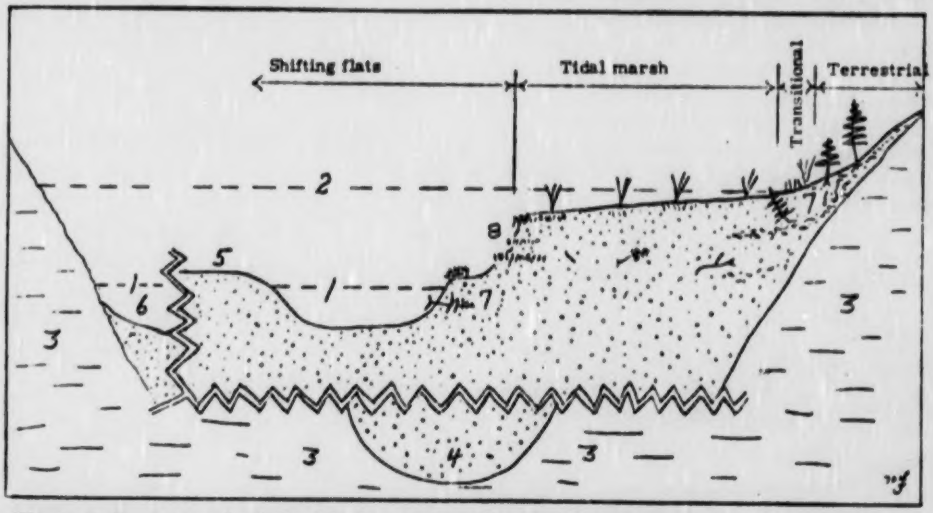


Figure 5 Some general relationships in a northern fjord with a rising water level. 1. mean low water, 2. maximum high tide, 3. Bedrock, 4. Glacial flour to depths in excess of 400 meters, 5. Shifting flats and channels, 6. Channel against bedrock, 7. Buried terrestrial vegetation, 8. Outcroppings of salt marsh peat.

b Low lying coastal plains tend to be fringed by barrier islands, broad estuaries and deltas, and broad associated marshlands (Figure 3).

Deep tidal channels fan out through innumerable branching and often interconnecting rivulets. The intervening grassy plains are essentially at mean high tide level.

c Tropical and subtropical regions such as Florida, the Gulf Coast, and Central America, are frequented by mangrove swamps. This unique type of growth is able to establish itself in shallow water and move out into progressively deeper areas (Figure 6). The strong deeply embedded roots enable the mangrove to resist considerable wave action at times, and the tangle of roots quickly accumulates a deep layer of organic sediment. Mangroves in the south may be considered to be roughly the equivalent of the Spartina marsh grass in the north as a land builder. When fully developed, a mangrove swamp is an impenetrable thicket of roots over the tidal flat affording shelter to an assortment of semi-aquatic organisms such as various molluscs and crustaceans, and providing access from the nearby land to predaceous birds, reptiles, and mammals. Mangroves are not restricted to estuaries, but may develop out into shallow oceanic lagoons, or upstream into relatively fresh waters.

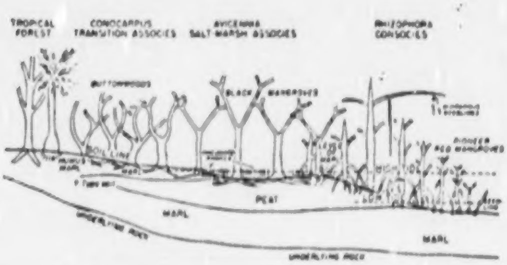


Figure 6 Diagrammatic transect of a mangrove swamp showing transition from marine to terrestrial habitat.

IV PRODUCTIVITY OF WETLANDS

A Measuring the productivity of grasslands is not easy, because today grass is seldom used directly as such by man. It is thus usually expressed as production of meat, milk, or in the case of salt marshes, the total crop of animals that obtain food per unit of area. The primary producer in a tidal marsh is the marsh grass, but very little of it is used by man as grass. (Table 1)

The nutritional analysis of several marsh grasses as compared to dry land hay is shown in Table 2.

TABLE 1. General Orders of Magnitude of Gross Primary Productivity in Terms of Dry Weight of Organic Matter Fixed Annually

Ecosystem	gms/M^2/year (grams/square meters/year)	lbs/acre/year
Land deserts, deep oceans	Tens	Hundreds
Grasslands, forests, eutrophic lakes, ordinary agriculture	Hundreds	Thousands
Estuaries, deltas, coral reefs, intensive agriculture (sugar cane, rice)	Thousands	Ten-thousands

TABLE 2. Analyses of Some Tidal Marsh Grasses

T/A	Percentage Composition					
Dry Wt.	Protein	Fat	Fiber	Water	Ash	N-free Extract
Distichlis spicata (pure stand, dry)						
2.8	5.3	1.7	32.4	8.2	6.7	45.5
Short *Spartina alterniflora* and *Salicornia europaea* (in standing water)						
1.2	7.7	2.5	31.1	8.8	12.0	37.7
Spartina alterniflora (tall, pure stand in standing water)						
3.5	7.6	2.0	29.0	8.3	15.5	37.3
Spartina patens (pure stand, dry)						
3.2	6.0	2.4	30.0	8.1	9.0	44.5
Spartina alterniflora and *Spartina patens* (mixed stand, wet)						
1.4	6.8	1.9	29.8	8.1	10.4	42.8
Spartina alterniflora (short, wet)						
2.2	8.8	2.4	30.4	8.7	13.3	36.3
Comparable Analyses for Hay						
1st cut	6.0	2.0	36.2	6.7	4.2	44.9
2nd cut	11.0	3.7	28.5	10.4	5.9	38.5

Analyses performed by Roland W. Gilbert, Department of Agricultural Chemistry, U.R.I.

B The actual utilization of marsh grass is accomplished primarily by its decomposition and ingestion by micro organisms. (Figure 7) A small quantity of seeds and solids is consumed directly by birds.

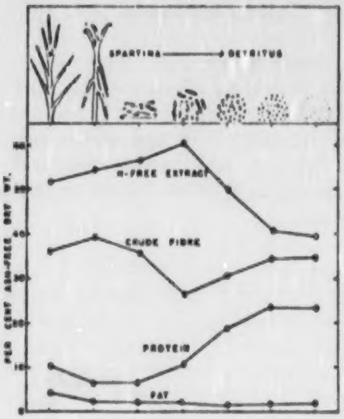


Figure 7 The nutritive composition of successive stages of decomposition of Spartina marsh grass, showing increase in protein and decrease in carbohydrate with increasing age and decreasing size of detritus particles.

1 The quantity of micro invertebrates which thrive on this wealth of decaying marsh has not been estimated, nor has the actual production of small indigenous fishes and invertebrates such as the top minnows (Fundulus), or the mud snails (Nassa), and others.

2 Many forms of oceanic life migrate into the estuaries, especially the marsh areas, for important portions of their life histories as is mentioned elsewhere (Figure 8). It has been estimated that in excess of 60% of the marine commercial and sport fisheries are estuarine or marsh dependent in some way.

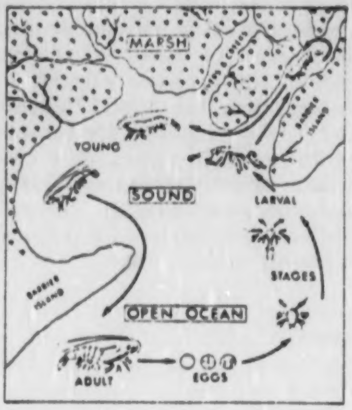
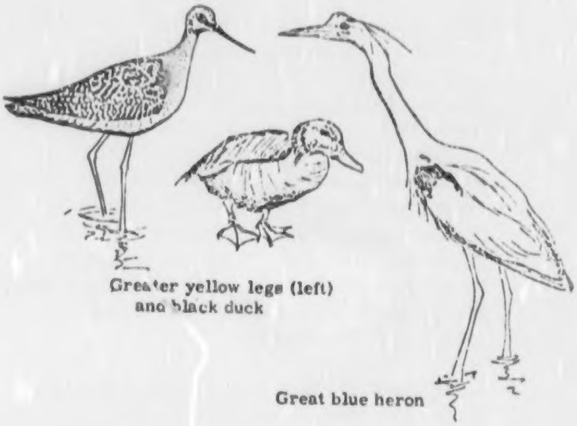


Figure 8 Diagram of the life cycle of white shrimp (after Anderson and Lunz 1965).

3 An effort to make an indirect estimate of productivity in a Rhode Island marsh was made on a single August day by recording the numbers and kinds of birds that fed on a relatively small area (Figure 9). Between 700 and 1000 wild birds of 12 species, ranging from 100 least sandpipers to uncountable numbers of seagulls were counted. One food requirement estimate for three-pound poultry in the confined inactivity of a poultry yard is approximately one ounce per pound of bird per day.



Greater yellow legs (left) and black duck

Great blue heron

Figure 9 Some Common Marsh Birds

One-hundred black bellied plovers at approximately ten ounces each would weigh on the order of sixty pounds. At the same rate of food consumption, this would indicate nearly four pounds of food required for this species alone. The much greater activity of the wild birds would obviously greatly increase their food requirements, as would their relatively smaller size.

Considering the range of foods consumed, the sizes of the birds, and the fact that at certain seasons, thousands of migrating ducks and others pause to feed here, the enormous productivity of such a marsh can be better understood.

V INLAND BOGS AND MARSHES

A Much of what has been said of tidal marshes also applies to inland wetlands. As was mentioned earlier, not all inland swamps are salt-free, any more than all marshes affected by tidal rythms are saline.

B The specificity of specialized floras to particular types of wetlands is perhaps more spectacular in freshwater wetlands than in the marine, where *Juncus*, *Spartina*, and Mangroves tend to dominate.

1 *Sphagnum*, or peat moss, is probably one of the most widespead and abundant wetland plants on earth. Deevey (1958) quotes an estimate that there is probably upwards of 223 billions (dry weight) of tons of peat in the world today, derived during recent geologic time from *Sphagnum* bogs. Particularly in the northern regions, peat moss tends to overgrow ponds and shallow depressions, eventually forming the vast tundra plains and moores of the north.

2 Long lists of other bog and marsh plants might be cited, each with its own special requirements, topographical, and geographic distribution, etc. Included would be the familiar cattails, spike rushes, cotton grasses, sedges, trefoils, alders, and many, many others.

C Types of inland wetlands.

1 As noted above (Cf: Figure 1) tidal marshes often merge into freshwater marshes and bayous. Deltaic tidal swamps and marshes are often saline in the seaward portion, and fresh in the landward areas.

2 River bottom wetlands differ from those formed from lakes, since wide flood plains subject to periodic inundation are the final stages of the erosion of river valleys, whereas lakes in general tend to be eliminated by the geologic processes of natural eutrophication often involving *Sphagnum* and peat formation. Riverbottom marshes in the southern United States, with favorable climates, have luxurient growths such as the canebrake of the lower Mississippi, or a characteristic timber growth such as cypress.

3 Although bird life is the most conspicuous animal element in the fauna (Cf: Figure 9), many mammals, such as muskrats, beavers, otters, and others are also marsh-oriented. (Figure 12)

Figure 12 Otter

VI POLLUTION

A No single statement can summarize the effects of pollution on marshlands as distinct from effects noted elsewhere on other habitats.

B Reduction of Primary Productivity

The primary producers in most wetlands are the grasses and peat mosses. Production may be reduced or eliminated by:

1 Changes in the water level brought about by flooding or drainage.

a Marshland areas are sometimes diked and flooded to produce freshwater ponds. This may be for aesthetic reasons, to suppress the growth of noxious marsh inhabitating insects such as mosquitoes or biting midges, to construct an industrial waste holding pond, a thermal or a sewage stabilization pond, a "convenient" result of highway causeway construction, or other reason. The result is the elimination of an area of marsh. A small compensating border of marsh may or may not develop.

b High tidal marshes were often ditched and drained in former days to stabilize the sod for salt hay or "thatch" harvesting which was highly sought after in colonial days. This inevitably changed the character of the marsh, but it remained as essentially marshland. Conversion to outright agricultural land has been less widespread because of the necessity of diking to exclude the periodic floods or tidal incursions, and carefully timed drainage to eliminate excess precipitation. Mechanical pumping of tidal marshes has not been economical in this country, although the success of the Dutch and others in this regard is well known.

2 Marsh grasses may also be eliminated by smothering as, for example, by deposition of dredge spoils, or the spill or discharge of sewage sludge.

3 Considerable marsh area has been eliminated by industrial construction activity such as wharf and dock construction, oil well construction and operation, and the discharge of toxic brines and other chemicals.

C Consumer production (animal life) has been drastically reduced by the deliberate distribution of pesticides. In some cases, this has been aimed at nearby agricultural lands for economic crop pest control, in other cases the marshes have been sprayed or dusted directly to control noxious insects.

1 The results have been universally disastrous for the marshes, and the benefits to the human community often questionable.

2 Pesticides designed to kill nuisance insects, are also toxic to other arthropods so that in addition to the target species, such forage staples as the various scuds (amphipods), fiddler crabs, and other macroinvertebrates have either been drastically reduced or entirely eliminated in many places. For example, one familiar with fiddler crabs can traverse miles of marsh margins, still riddled with their burrows, without seeing a single live crab.

3 DDT and related compounds have been "eaten up the food chain" (biological magnification effect) until fish eating and other predatory birds such as herons and egrets (Figure 9), have been virtually eliminated from vast areas, and the accumulation of DDT in man himself is only too well known.

D Most serious of the marsh enemies is man himself. In his quest for "lebensraum" near the water, he has all but killed the water he strives to approach. Thus up to twenty percent of the marsh--estuarine area in various parts of the country has already been utterly destroyed by cut and fill real estate developments (Figures 10, 11).

E Swimming birds such as ducks, loons, cormorants, pelicans, and many others are severely jeopardized by floating pollutants such as oil.

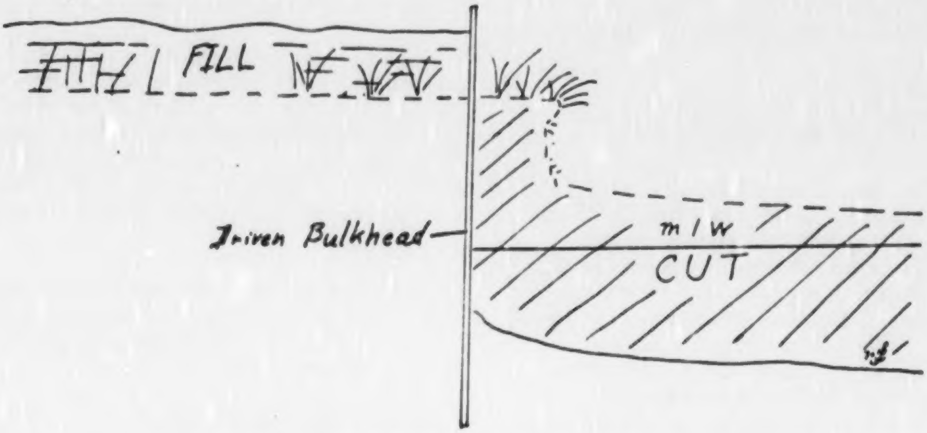


Figure 10. Diagrammatic representation of cut-and-fill for real estate development. mlw = mean low water

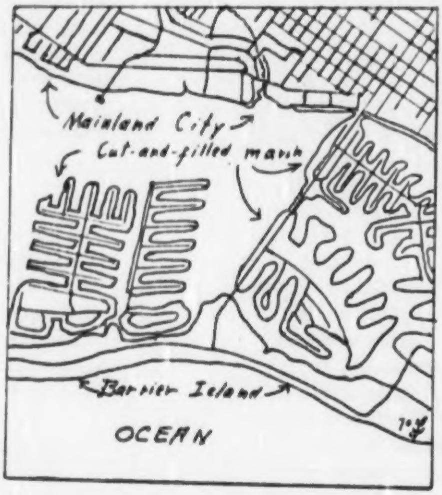


Figure 11. Tracing of portion of map of a southern city showing extent of cut-and-fill real estate development.

VII SUMMARY

A Wetlands comprise the marshes, swamps, bogs, and tundra areas of the world. They are essential to the well-being of our surface waters and ground waters. They are essential to aquatic life of all types living in the open waters. They are essential as habitat for all forms of wildlife.

B The tidal marsh is the area of emergent vegetation bordering the ocean or an estuary.

C Marshes are highly productive areas, essential to the maintenance of a well rounded community of aquatic life.

D Wetlands may be destroyed by:

1 Degradation of the life forms of which it is composed in the name of nuisance control.

2 Physical destruction by cut-and-fil. to create more land area.

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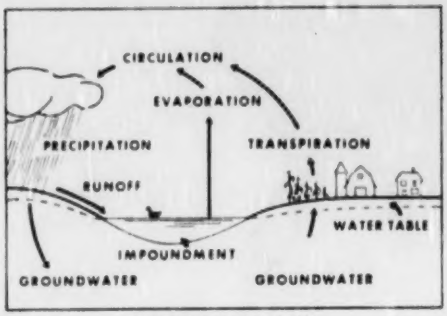
Descriptors: Aquatic Environment, Estuarine Environment, Lentic Environment Lotic Environment, Currents, Marshes, Limnology

WATER RESOURCES AND NEEDS

I WATER RESOURCES

A The source of all freshwater is the hydrologic cycle, shown in Figure 1.



THE HYDROLOGIC CYCLE

Figure 1

1 Precipitation of water as rain, snow, hail, sleet or dew.

2 Percolation of water through soil to an aquifer to form groundwater.

3 Runoff of water which forms lakes, streams and rivers.

4 Evaporation of surface water or transpiration of water from green plants to the atmosphere.

5 Atmospheric recirculation of the water vapor.

B The world's supply of water is contained within the hydrologic cycle as:

1 Oceanic water

2 Water vapor in the atmosphere

3 Ice and snow in glaciers and snowpack

4 Runoff water in lakes and streams

5 Groundwater

C Withdrawals for use are mostly from those waters in the runoff and groundwater phases, although some oceanic waters are being utilized.

D Precipitation--which serves to recharge groundwaters and surface supplies--is at a relatively fixed annual rate.

1 Average precipitation in the U.S. is 30 inches per year or 4,200-4,400 billion gallons per day.

2 Evapo-transpiration losses total approximately 21 inches per year or approximately 2,940 billion gallons per day.

3 The available water totals approximately 9 inches per year or 1,260 billion gallons per day.

II THE DISTRIBUTION OF U.S. WATER RESOURCES

Although the water supply in the hydrologic cycle is fixed in amount, it is not distributed evenly. A wide disparity of water distribution exists both in time and space. Distribution of the annual average precipitation is shown in Figure 2.

A Distribution of Precipitation

1 Dependent upon:

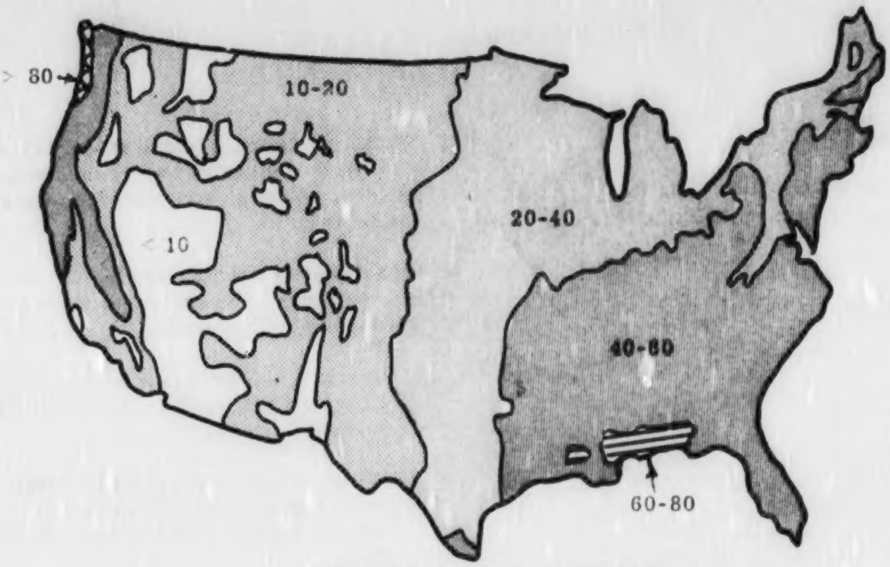
a Atmospheric conditions such as temperature and winds

b The geography of the region

c The general climate of the area

2 U.S. areas of high annual precipitation

a The Pacific slope varies from 10 inches to greater than 100 inches annually.



Distribution of Precipitation
(Average Annual)
Inches

Figure 2

- b The gulf states precipitation varies from 20 to 60 inches annually.
- c Precipitation in the midwest and Great Lakes area ranges from 25 to 50 inches per year.
- d Precipitation along the Atlantic Coast averages between 35 to 50 inches per year.

3 Areas of low annual precipitation

- a The Rocky Mountain area precipitation ranges between 10 and 20 inches per year.
- b Much of the southwest has less than 10 inches of precipitation annually.

4 Distribution of precipitation with time

- a The rainy or wet season varies from summer to winter, or in some areas there is relatively little change e year.
- b Local storms of high intensity may reach as much as 30 inches in 24 hours.

B Distribution of Runoff

1 Dependent upon:

- a Precipitation in the region
- b Infiltration - which is controlled by the geologic formations and the time lapse between rains.
- c Season of the year controls evaporation, and snow melt.
- d Topography controls the time available to percolate through the soil.
- e Vegetation type and density affects interception and evapotranspiration.

2 Areas of high annual runoff

- a Sections of the Pacific slope have greater than 80 inches annually.

b The eastern 1/3 of the U.S. averages greater than 20 inches of runoff annually.

3 Much of the western U.S. has less than 1 inch of runoff annually.

a Southwest

b Rocky Mountain states

c Rocky Mountain plateau

4 Time distribution of runoff

a Overflow--runoff during and immediately following precipitation.

b Base flow--sustained or fair weather runoff composed of delayed subsurface and groundwater runoff. See Figure 3 for runoff cycle.

C Distribution of Groundwater

1 Groundwater volume is affected by the same factors as runoff.

2 Geologic formations and soils control percolation and storage of groundwater.

3 Topography controls time available for percolation.

4 Evapo-transpiration varies with the season, as does precipitation and ground saturation.

III WATER USE

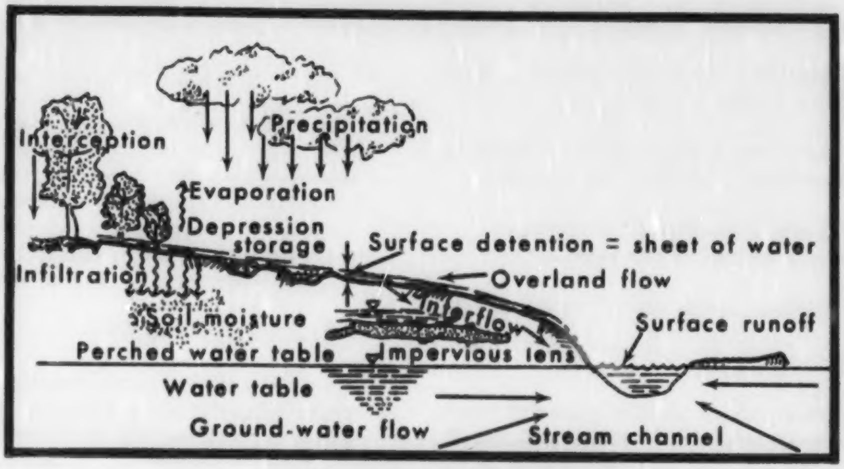
A Present Water Use in the U.S.

1 Water available for use

a Nine inches or 1,160 billion gallons per day are not lost through evapo-transpiration, and is therefore theoretically available.

b Water use in the U.S. at the present time is approximately 390 billion gallons per day or 3 inches of our total supply.

c Twenty-one inches are lost through evapo-transpiration.



THE RUNOFF CYCLE
(Davis & DeWiest)
Figure 3

2 The way in which water is used

Water uses can be grouped into two classes. Those uses which are in situ such as recreation, fishing, and wildlife and those uses requiring withdrawal from the stream. These withdrawals are:

a Agricultural uses take 46% of our supply or 180 billion gallons/day; only 40% of this water is returned to the streams.

b Industrial uses take another 46% of our supply. 2% of the water used by industry is consumed.

c Municipal uses total approximately 25 billion gallons daily or 8% of the total.

3 Source of water used in U.S.

a National averages show 80% or 312 billion gallons per day to be from surface sources, while 20% is taken from the ground.

b The ratio of surface water to groundwater varies and is dependent on the quantity and quality available in each locality, as well as the cost.

4 Seasonal uses of water

a Irrigation waters are used during the growing season only.

b Some water using industries such as the canning industry are seasonal.

c The majority of industries needs water throughout the year.

d Municipal use is higher in the summer.

B Demand for water is increasing

1 The predicted demand of water in 1980 is approximately 600 billion gallons of water per day, or 220,000 billion per year.

2 This is mainly due to expansion of industry and irrigated agriculture.

3 Much of the demand for water will be in areas such as the southwest, that are already short on water.

C Methods for the Development of U.S. Water Resources for Future Needs

1 Utilization of our present sources of water, surface and groundwater, must be increased. This would mean increased storage, both on the surface and in underground reservoirs.

2 Desalinization of ocean waters and brackish waters holds some promise for regions where transportation will not be expensive.

3 Reduction of evapo-transpiration losses will greatly increase our total available supply.

4 Weather modification methods could possibly give us precipitation in the right place at the right time.

5 Greater reuse of our present supply is both through multiple use and better waste treatment methods.

IV SUMMARY

The total amount of water available appears to be fixed. In view of the increasing demands and the currently inefficient utilization of the supply, the demand may very shortly exceed the supply. Better management of the resource and more engineering research are urgently needed.

ACKNOWLEDGEMENT:

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Table 1. AVAILABILITY OF GROUND WATER

	Areas	Water Use (excluding water power) Use in mgd and Percent of total from Ground Water Sources	
		Total mgd	Ground water (%)
A	Atlantic and Gulf Coastal Plain area	32,000	25
B	Southern Great Plains area	21,000	45
C	Appalachian Mountain and Piedmont area	8,000	50
D	Rocky Mountains, northern Great Plains, and northern Pacific Coast area	28,000	12
E	Unglaciated central plateaus and lowlands	26,000	10
F-1	Basin and range	41,000	42
F-2	Columbia Plateau	24,000	7
G	Glaciated area of the East and Midwest	57,000	10
	U.S. Total (rounded)	240,000	20

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TECHNIQUES FOR THE BIOLOGICAL EVALUATION OF POLLUTANTS

I INTRODUCTION

A Ways in Which Wastes Affect Aquatic Life

1 Indirect: by modification of the environment such as by modifying food chain, changing average annual temperature, or reducing DO.

2 Direct: physical or physiological action on the organism itself.

3 Rendering aquatic product distasteful or dangerous for human consumption.

B Two Basic Approaches: field observation, or laboratory tests.

NOTE: Equipment and procedures for making the following determinations and interpretations of results, will not be considered.

II FIELD OBSERVATIONS

A Field evaluations are usually based on comparisons with an actual or imaginary unpolluted reference or "control" site. For example, what are the actual conditions:

1 In a stream below a point of pollution as compared to above (an actual or real control).

2 In any polluted area compared to "what it might, or should be" (this is a theoretical control, depends on the skill and integrity of the evaluator for its usefulness).

3 In any polluted area, what are conditions now as compared to what they were before pollution was introduced? This assumes that a pre-pollution study or observation was made, which in this case constitutes the control.

Field controls in general are much less rigorous than laboratory controls. Liberal margins of safety must thus be provided when extrapolating laboratory results to field conditions.

B Two general types of biological evaluations may be employed in the above comparisons: qualitative (descriptive) and quantitative (measurement).

1 Qualitative observation

a The indicator concept is generally based on the positive thought that there must be some organism which is found in polluted areas but not in unpolluted areas.

1) This is true only for the bacteria where certain forms present in the intestines of warm-blooded animals can be found in sewage. Finding and identifying these organisms thus demonstrates a strong likelihood that animal excrement is present.

2) Higher forms of life do not usually live in the sources of pollution, especially industrial, and hence are not carried thence into the receiving water. There is no known form of pollution-tolerant higher life which cannot also be found in unpolluted places. The finding of a pollution-tolerant organism does not therefore necessarily demonstrate pollution. There is, however, infinite variety to the sensitivity of various forms of higher life to the various forms of pollution.

b Population balance, that is, the species composition of the aquatic community, is very sensitive to environmental conditions, and hence to pollution.

2 Quantitative observation and measurements

a Quantitative data may have reference to the entire aquatic community, or only to selected or individual species. Reference may be to numbers or to weight. Weight may be wet, dry, ashed, etc. Rate of production may be involved. Much remains to be done in this field.

b Productivity is the ability of an environment to produce or grow a crop of organisms (corn, hogs, algae, fish, mayflies). Productivity may be measured in some stipulated unit of quantity per unit of volume or area per unit of time. For example:

- Grams of carbon fixed (by photosynthesis) per square meter per day;
- Pounds of fish produced per acre per year;
- Number of fish catchable per fisherman-hour.

c The standing crop is an estimate of the quantity (or biomass) of some specified portion of the aquatic community present at a point in time. For example:

- Pounds of large mouthed black bass per acre;
- Grams of pollution-intolerant bottom invertebrates per square foot, square meter, etc.;
- Total plankton count per ml, or per liter
- Total quantity of all life present per unit area, volume, etc.

3 Various workers have developed formulas for expressing the degree or nature of pollution based on one or more of the above determinations. While valid and useful in the hands of the originator and his staff, none has yet been universally accepted.

III LABORATORY EVALUATIONS

These, too, almost invariably involve a comparison or "control" setup. Such studies may have broad and general objectives, or be designed to detect life history stages exhibiting maximum sensitivity such as eggs, juveniles, breeding condition, etc.

A Bioassays are assays of the biological effect of something, employing living organisms as the yardstick. They are widely employed in commercial, scientific, and water quality surveillance activities.

1 Methods useful for aquatic organisms are described in Standard Methods. Test organisms are exposed to a series of concentrations of some substance for a stated period of time under stated conditions.

a If the material is highly toxic in the concentrations employed and the organisms in the higher concentrations die, "tolerance limits" can be calculated. A common parameter employed is the concentration which 50% of the organisms can tolerate (or survive) for time "t" called the "median tolerance limit" (for time "t"). This may be written "TL_m"96hrs. for the 96 hour median tolerance limit, for example.

b Any appropriate organism may be employed, from protozoa to fish.

2 "Static jars" or "continuous flow" apparatus may be employed to provide the various dilutions of the toxicant being tested.

a Static jar tests are seldom run for more than a week, and are usually read only in terms of percent survival or kill, generally termed "acute" toxicity.

b Continuous flow apparatus may likewise be employed to measure short term acute toxicity, but it is virtually essential for long term tests at sublethal concentrations where parameters other than lethal thresholds, at given time intervals, are measured; e.g., tests of a series of sublethal concentrations of a toxicant on the growth rate and breeding success of a species of fish, lasting for one or two years.

B A recently published procedure called biomonitoring provides for the continuous surveillance of an industrial effluent (or a dilution thereof) using live organisms as the test of its suitability for discharge.

C A conventional BOD determination is a bioassay of biologically oxidizable material present.

D Combination laboratory and field studies are often conducted to determine the effects of specific substances or conditions, often on specific organisms; for example, the effect of heated water discharges on oysters, or the effect of endrin on catfishes.

E Post mortem examination of dead organisms, especially fishes, can occasionally shed light on the cause of death. For example, the ratio of zinc in the gill structure to zinc in the opercular bone can indicate death caused by a sudden increase in the zinc concentration of the water. Unfortunately, relatively few substances have been so analyzed.

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SIGNIFICANCE OF "LIMITING FACTORS" TO POPULATION VARIATION

I INTRODUCTION

A All aquatic organisms do not react uniformly to the various chemical, physical and biological features in their environment. Through normal evolutionary processes various organisms have become adapted to certain combinations of environmental conditions. The successful development and maintenance of a population or community depend upon harmonious ecological balance between environmental conditions and tolerance of the organisms to variations in one or more of these conditions.

B A factor whose presence or absence exerts some restraining influence upon a population through incompatibility with species requirements or tolerance is said to be a limiting factor. The principle of limiting factors is one of the major aspects of the environmental control of aquatic organisms (Figure 1).

II PRINCIPLE OF LIMITING FACTORS

This principle rests essentially upon two basic concepts. One of these relates organisms to the environmental supply of materials essential for their growth and development. The second pertains to the tolerance which organisms exhibit toward environmental conditions.

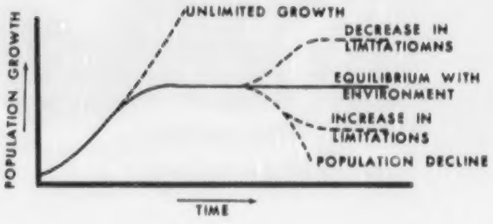

Figure 1. The relationships of limiting factors to population growth and development.

A Liebig's Law of the Minimum enunciates the first basic concept. In order for an organism to inhabit a particular environment, specified levels of the materials necessary for growth and development (nutrients, respiratory gases, etc.) must be present. If one of these materials is absent from the environment or present in minimal quantities, a given species will only survive in limited numbers, if at all (Figure 2).

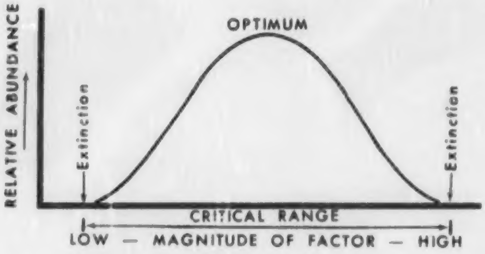

Figure 2. Relationships of environmental factors and the abundance of organisms.

1 The subsidiary principle of factor interaction states that high concentration or availability of some substance, or the action of some factor in the environment, may modify utilization of the minimum one. For example:

a The uptake of phosphorus by the algae Nitzchia closterium is influenced by the relative quantities of nitrate and phosphate in the environment; however, nitrate utilization appears to be unaffected by the phosphate (Reid, 1961).

b The assimilation of some algae is closely related to temperature.

c The rate of oxygen utilization by fish may be affected by many other substances or factors in the environment.

d Where strontium is abundant, mollusks are able to substitute it, to a partial extent, for calcium in their shells (Odum, 1959).

2 If a material is present in large amounts, but only a small amount is available for use by the organism, the amount available and not the total amount present determines whether or not the particular material is limiting (calcium in the form of $CaCO_3$).

B Shelford pointed out in his Law of Tolerance that there are maximum as well as minimum values of most environmental factors which can be tolerated. Absence or failure of an organism can be controlled by the deficiency or excess of any factor which may approach the limits of tolerance for that organism (Figure 3).

Minimum Limit of Toleration		Range of Optimum of Factors	Maximum Limit of Toleration	
Absent	Decreasing Abundance	Greatest Abundance	Decreasing Abundance	Absent

Figure 3. Shelford's Law of Tolerance.

1 Organisms have an ecological minimum and maximum for each environmental factor with a range in between called the critical range which represents the range of tolerance (Figure 2). The actual range thru which an organism can grow, develop and reproduce normally is usually much smaller than its total range of tolerance.

2 Purely deleterious factors (heavy metals, pesticides, etc.) have a maximum tolerable value, but no optimum (Figure 4).

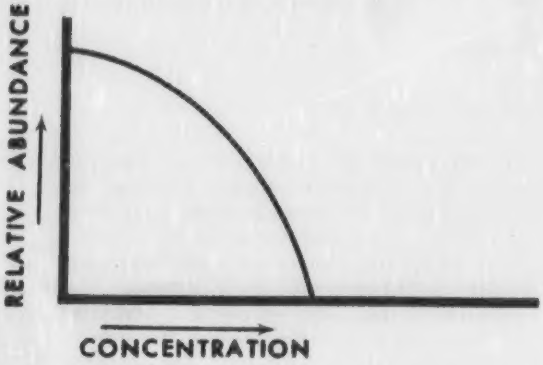

Figure 4. Relationship of purely harmful factors and the abundance of organisms.

3 Tolerance to environmental factors varies widely among aquatic organisms.

a A species may exhibit a wide range of tolerance toward one factor and a narrow range toward another. Trout, for instance, have a wide range of tolerance for salinity and a narrow range for temperature.

b All stages in the life history of an organism do not necessarily have the same ranges of tolerance. The period of reproduction is a critical time in the life cycle of most organisms.

c The range of tolerance toward one factor may be modified by another factor. The toxicity of most substances increases as the temperature increases.

d The range of tolerance toward a given factor may vary geographically within the same species. Organisms that adjust to local conditions are called ecotypes.

e The range of tolerance toward a given factor may vary seasonally. In general organisms tend to be more sensitive to environmental changes in summer than in other seasons. This is primarily due to the higher summer temperatures.

4 A wide range of distribution of a species is usually the result of a wide range of tolerances. Organisms with a wide range of tolerance for all factors are likely to be the most widely distributed, although their growth rate may vary greatly. A one-year old carp, for instance, may vary in size from less than an ounce to more than a pound depending on the habitat.

5 To express the relative degree of tolerance for a particular environmental factor the prefix eury (wide) or steno (narrow) is added to a term for that feature (Figure 5).

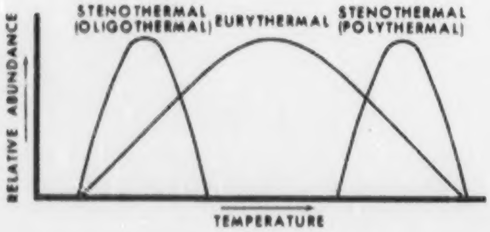

Figure 5. Comparison of relative limits of tolerance of stenothermal and eurythermal organisms.

C The law of the minimum as it pertains to factors affecting metabolism, and the law of tolerance as it relates to density and distribution, can be combined to form a broad principle of limiting factors.

1 The abundance, distribution, activity and growth of a population are determined by a combination of factors, any one of which may through scarcity or overabundance be limiting.

2 The artificial introduction of various substances into the environment tends to eliminate limiting minimums for some species and create intolerable maximums for others.

3 The biological productivity of any body of water is the end result of interaction of the organisms present with the surrounding environment.

III VALUE AND USE OF THE PRINCIPLE OF LIMITING FACTORS

A The organism-environment relationship is apt to be so complex that not all factors are of equal importance in a given situation; some links of the chain guiding the organism are weaker than others. Understanding the broad principle of limiting factors and the subsidiary principles involved make the task of ferreting out the weak link in a given situation much easier and possibly less time consuming and expensive.

1 If an organism has a wide range of tolerance for a factor which is relatively constant in the environment that factor is not likely to be limiting. The factor cannot be completely eliminated from consideration, however, because of factor interaction.

2 If an organism is known to have narrow limits of tolerance for a factor which is also variable in the environment, that factor merits careful study since it might be limiting.

B Because of the complexity of the aquatic environment, it is not always easy to isolate the factor in the environment that is limiting a particular population. Premature conclusions may result from limited observations of a particular situations. Many important factors may be overlooked unless a sufficiently long period of time is covered to permit the factors to fluctuate within their ranges of possible variation. Much time and money may be wasted on control measures without the real limiting factor ever being discovered or the situation being improved.

C Knowledge of the principle of limiting factors may be used to limit the number of parameters that need to be measured or observed for a particular study. Not all of the numerous physical, chemical and biological parameters need to be measured or observed for each study undertaken. The aims of a pollution survey are not to make and observe long lists of possible limiting factors but to discover which factors are significant, how they bring about their effects, the source or sources of the problem, and what control measures should be taken.

D Specific factors in the aquatic environment determine rather precisely what kinds of organisms will be present in a particular area. Therefore, organisms present or absent can be used to indicate environmental conditions. The diversity of organisms provides a better indication of environmental conditions than does any single species. Strong physio-chemical limiting factors tend to reduce the diversity within a community; more tolerant species are then able to undergo population growth.

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THE ADVENT OF THERMAL POLLUTION

I INTRODUCTION

A The problem of thermal pollution has impinged upon our consciousness because of the tremendous growth in the use of electric energy, in the size of the central electricity generating stations, and the transition from fossil fuels to nuclear fuels.

B Thermal pollution has been defined as man caused deleterious changes in the normal temperature of water.

C Human activity can change the normal temperature of water in many ways. Temperature changes may be induced by altering the environment of the watercourse through:

1 Road building

2 Logging

3 Creating impoundments

4 Diverting flows for irrigation

D Water temperature may also be changed directly by adding or taking away heat.

E The first questions we must ask are how serious is the thermal pollution problem and what is the magnitude of the problem.

II WASTE HEAT: THE PROBLEM

A Present and future demands indicate that industrial cooling water, when viewed nationally, is the most important source of waste heat.

B Of this industrial source, electric power generating industry alone accounts for about 80 percent of the cooling water used.

C The best single index of the thermal pollution potential lies in projecting future electric power production.

1 Power generation has approximately doubled each ten years during this century.

2 Future demands indicate a shortening of the time span for similar increases.

D Waste heat output has not multiplied as fast as power generation because of improvements in thermal plant efficiency and development of hydropower.

E Fossil-fueled plants are reaching a limit of efficiency and nuclear plants are even less efficient than fossil-fueled ones.

F With these considerations in mind, heat rejection from the predicted mixture of nuclear and fossil power plants is expected to increase almost ninefold by the year 2000.

G Waste heat from industry will also increase.

III MANAGING WASTE HEAT

A The problem is one of managing tremendous amounts of waste heat in a manner that will maintain the physical, chemical, and biological nature of our water resources.

B Water quality standards are being implemented to protect these resources.

C Thermal pollution control measures are costly and complicated.

1 Federal Water Quality Administration estimated the cost of cooling facilities needed over the five years--1968 through 1972--at 1.8 billion dollars.

2 By comparison, in one year alone (1965), 3 billion dollars was spent on sport fishing.

3 Thus the potential effect of thermal pollution on this and other beneficial water uses must be considered.

IV MODIFICATIONS OF THE ENVIRONMENT BY HEAT WASTES

A Changes can be noted as the thermal regime of rivers, lakes, and reservoirs change. These changes effect the ecology and these effects are usually for the worse.

1 Heat killing fish

2 Sublethal effects

B Though only a small number of fish kills due to thermal changes have occurred to date, if unrestricted use of streams, lakes, and reservoirs for cooling purposes were allowed, the number would greatly increase. Therefore, the concern is primarily to prevent a potential major pollution problem from occurring.

C Discharging heated waters is equivalent to discharging organic wastes in the lowering of the assimilative capacity of a stream.

D The cooling water requirements for even a 20°F rise is greater than the minimum daily flow of the Mississippi River at Vicksburg (Mathur, 1968).

V SUMMARY

We must develop a thorough understanding of the causes, effects, and control of thermal pollution in order to apply equitable, reasonable and effective approaches toward its solution.

ACKNOWLEDGMENT

Portions of this outline were taken from "The Industrial Waste Guide on Thermal Pollution," Alden G. Christianson and Bruce A. Tichenor, principal authors and "Thermal Pollution: Status of the Art," Frank L. Parker and Peter A. Krenkel, authors.

This outline was prepared by John F. Wooley, Biologist, Manpower and Training Branch, Pacific Northwest Water Laboratory, FWQA.

GENERAL EFFECTS OF TEMPERATURE ON AQUATIC ORGANISMS

I INTRODUCTION

A Water temperature plays a major role in the ability of any waterbased ecological system to maintain optimum characteristics throughout all biological stages. Temperature effects on all organisms in an aquatic community are important because of the interdependence of species.

1 For example, temperatures which are not lethal to fish or shellfish may affect metabolism, reproduction and growth, as well as reduce important food organisms, thereby inducing a change in the balance of the entire system.

2 All natural biological systems are highly complex; hence it is very difficult and potentially misleading to generalize on the effect temperature changes have on the aquatic biota. A more realistic approach is to direct investigations to locally important species.

B The scientific literature contains a large volume of information on the effect of temperature on all levels of the aquatic biota.

1 Data are given which indicate maximum temperatures, optimum temperature ranges, maximum permissible temperature changes, acclimation temperatures, etc., for a wide variety of organisms.

2 These data are based upon both laboratory and field investigations of various degrees of depth.

C The information presented on the biological effects of thermal pollution is not complete. Hopefully, however, it will be useful in detecting potential biological problems associated with water temperature changes. Where such problems are anticipated, a complete analysis of the situation, tailored to the specific site and problem, is needed.

II KNOWN EFFECTS OF TEMPERATURE

A The response of aquatic organisms to elevated water temperatures has been studied in the laboratory and in situ by experts in many scientific disciplines.

B These well documented responses are:

1 A shift in population structure of the ecosystem

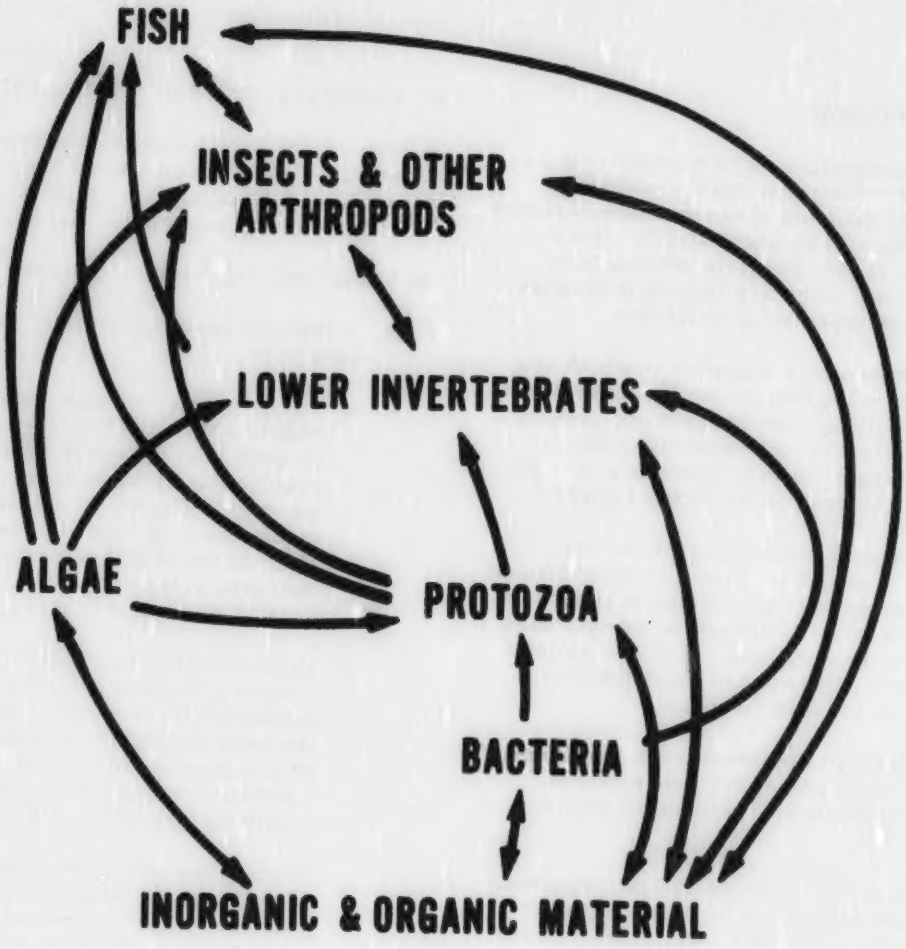
a The structure of aquatic communities, often called the "food web" (Figure 1) is the result of the relationship between organisms and the environment as well as among the organisms themselves. Most forms of stress cause a decrease in the complexity of the aquatic community (Cairns, 1967).

b Patrick (1949) demonstrated the effects of organic pollution on population diversity by comparing the total number of species in each of seven taxonomic groups with the number in that group at stations relatively free of pollution.

Typical results for various degrees of pollution are shown in Figure 2, with the related taxonomic grouping or organisms and interpretation of results in Table 1.

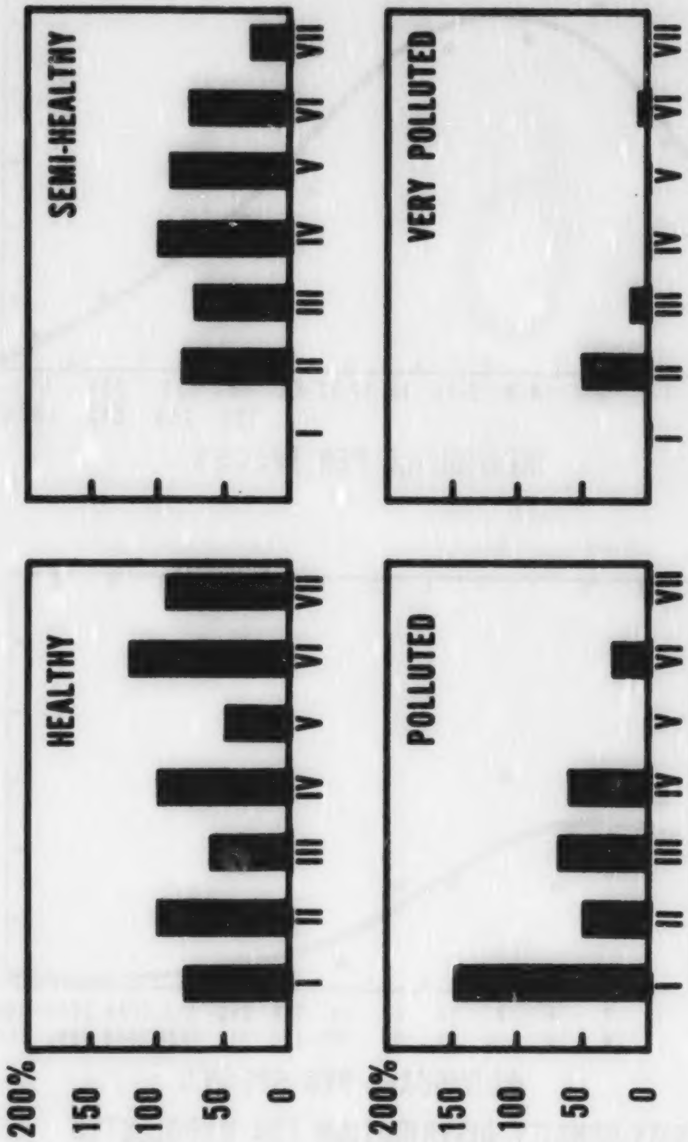
c Patrick et al (1954) also examined the effects of pollution on the diversity of the diatom population. Diversity-density distribution plots for an unpolluted stream and for a polluted one appear in Figure 3.

2 The above examples indicate that a healthy aquatic community is one in which many species are present, with each species having few individuals; while under stressed conditions, fewer



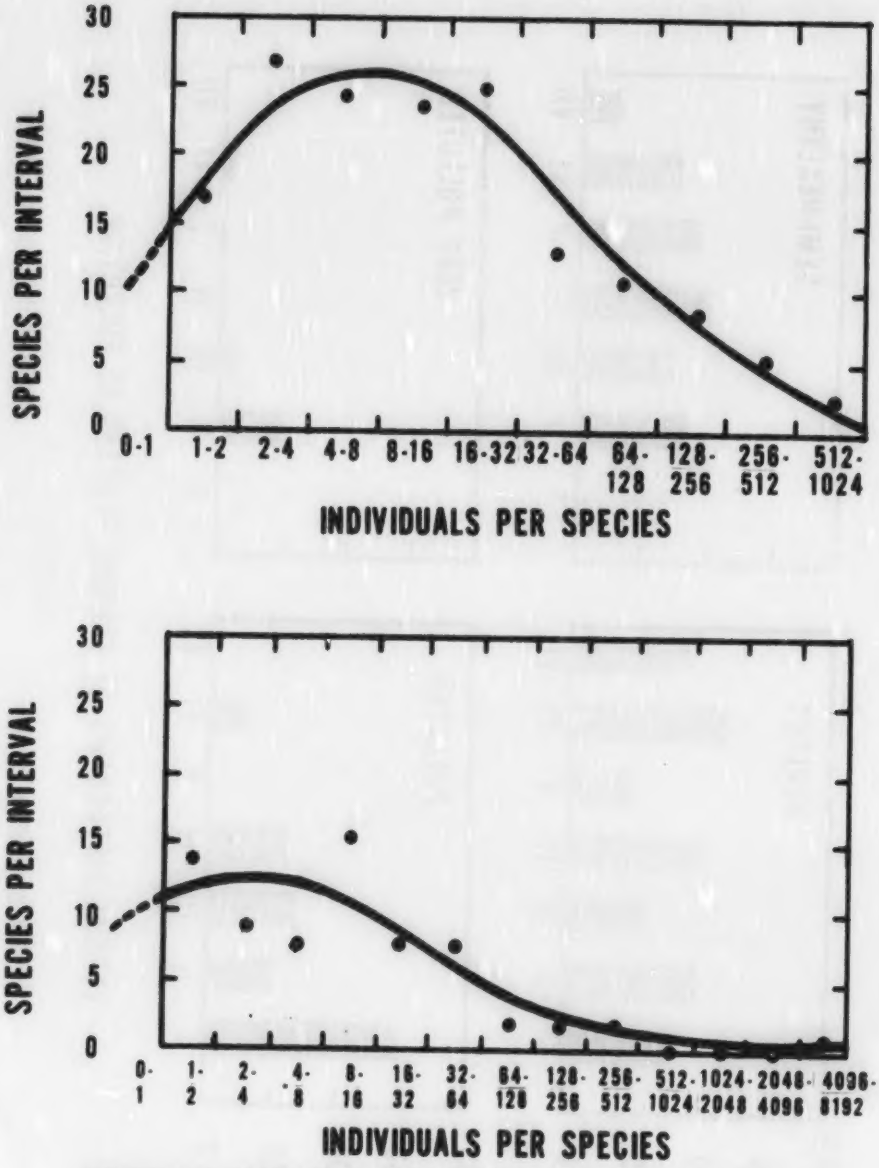
SIMPLIFIED AQUATIC FOOD WEB

FIGURE 1



TYPICAL HISTOGRAMS OF VARIOUS DEGREES OF POLLUTION

FIGURE 2



DIVERSITY-DENSITY DISTRIBUTION FOR UNPOLLUTED (UPPER CURVE) AND POLLUTED (LOWER CURVE) STREAMS

FIGURE 3

TABLE 1

TAXONOMIC GROUPING OF ORGANISMS AND INTERPRETATION OF RESULTS OF PATRICK'S SYSTEM OF BIOLOGICAL MEASUREMENT OF STREAM CONDITION

Column	Organisms
I	The blue-green algae, Stigeoclonium, Spirogyra, Tribonema, and certain rotifers
II	Oligochaetes, leeches and pulmonate snails
III	Protozoa
IV	Diatoms, red algae, and most green algae
V	All rotifers not included in I plus clams, prosobranch snails and tricladid worms
VI	All insects and crustacea
VII	All fish

Stream Conditions	Results
Healthy	Col. IV, VI and VII all above 50 percent
Semi-Healthy	(a) Either or both Col. VI or VII below 50 percent and Col. I or II under 100 percent, or
	(b) Either Col. VI or VII below 50 percent, and Col. I, II and IV 100 percent or over, or over, or Col. IV is double width
Polluted	(a) If either or both of Col. VI and VII are absent, and Col. I and II are 50 percent or better, or
	(b) If Col. VI and VII are both present, but below 50 percent then Col. I and II must be 100 percent or more
Very polluted	(a) If Col. VI and VII are absent and Col. IV is below 50 percent, or
	(b) If Col. VI or VII is present, but Col. I or II is less than 50 percent

species are present with large numbers of individuals per species.

D Wurtz and Dolan (1960) concluded from the results of a study on a stretch of the Schuylkill River into which heated water was discharged, that the hot water discharge reduced the diversity of the prevailing biological structure of the river.

III DEATH BEYOND CERTAIN TEMPERATURES

A Extremes of temperature which can be endured by fishes have been studied since the 1940's (Brett, 1960), with considerably more emphasis on upper lethal temperatures than on lower ones.

1 Comprehensive tables of lethal temperatures and the associated acclimatization temperatures for a large number of species have been compiled by Jones (1964), McKee and Wolf (1963), Mason (1962), FWPCA (1967), and DeSylva (1969).

B The lethal temperature has been found to be a function of many factors, including diet, activity, age, general health, osmotic stress, and weather.

1 This large number of variables makes it difficult to determine a useful value for the lethal temperature since the lethal temperature changes somewhat with variations in each of those variables.

2 The aquatic species, its thermal history, and the exposure time are major factors which affect lethal temperature levels.

C The tables mentioned above demonstrate the variety of thermal limits among the fishes.

1 Brett (1952) demonstrated the variance of these limits among seven species acclimated to the same temperature, using data from three authors (Figure 4).

2 In the same figure, the effect of exposure time on the upper lethal limit for each of the species is shown.

3 The fact that the semi-logarithmic plots of temperature versus time to 50% mortality are reasonably parallel is noteworthy.

D The effect of acclimatization (thermal history) and exposure time on upper lethal limits for a single species is shown in Figure 5.

E The extremes of temperature which can be tolerated indefinitely by a species and their dependence on acclimatization temperature can be summarized in a "tolerance trapezium" similar to Brett's (1960), which appears in Figure 6.

1 It is significant that the difference between the 50% - and 5% - lethal levels is small, indicating that a large increase in mortality can result from a small change in temperature near the tolerance limits (Brett, 1958).

IV SUBLETHAL FUNCTIONAL RESPONSE

A Extreme temperature is a killer, but within the zone of tolerance temperature is:

1 A catalyst

2 A depressant

3 An activator

4 A restrictor

5 A stimulator

6 A controller

B Temperature is one of the most important and influential water quality characteristics to life in water (Federal Water Pollution Control Administration, 1967).

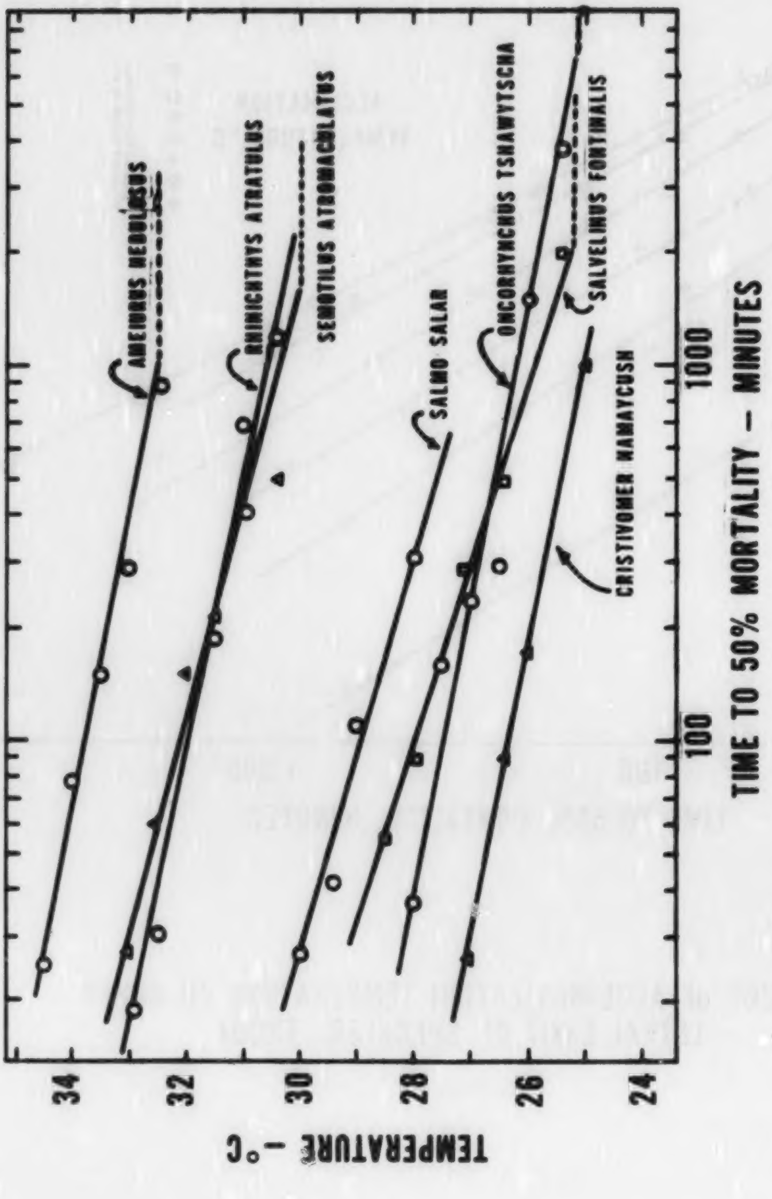
C Brett (1969) recognized the limiting capability of temperature on fishes when he produced the "tolerance trapezium" (Figure 6).

1 Well within the zone of tolerance lies a smaller zone outside which activity and growth are limited.

2 Within that zone lies an even smaller one which defines the temperatures which allow normal reproduction.

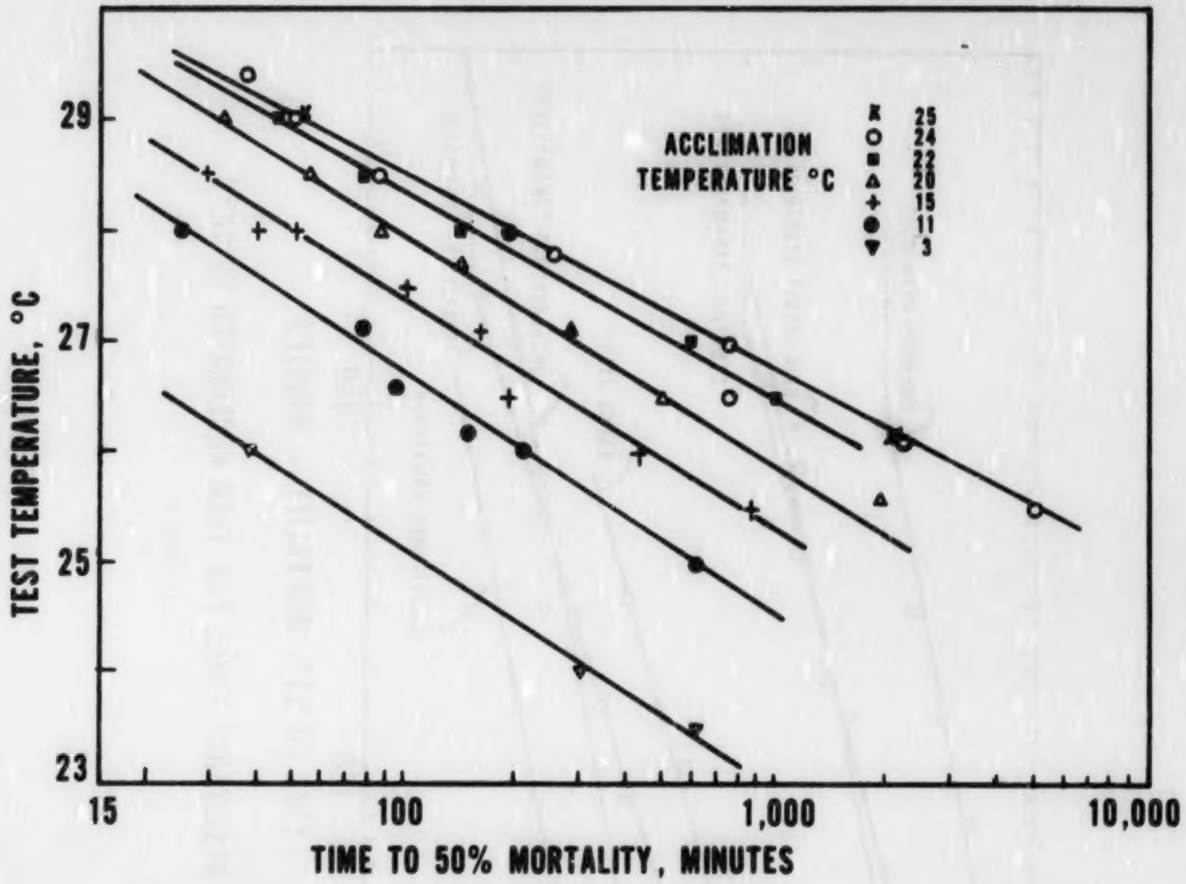
3 Although the boundaries of the smaller zones are not as well defined as those of the tolerance zone, their significance is recognized.

D The relationship between rate of metabolism and temperature for two species is shown in Figures 7 and 9 (Fry and Hart, 1948).



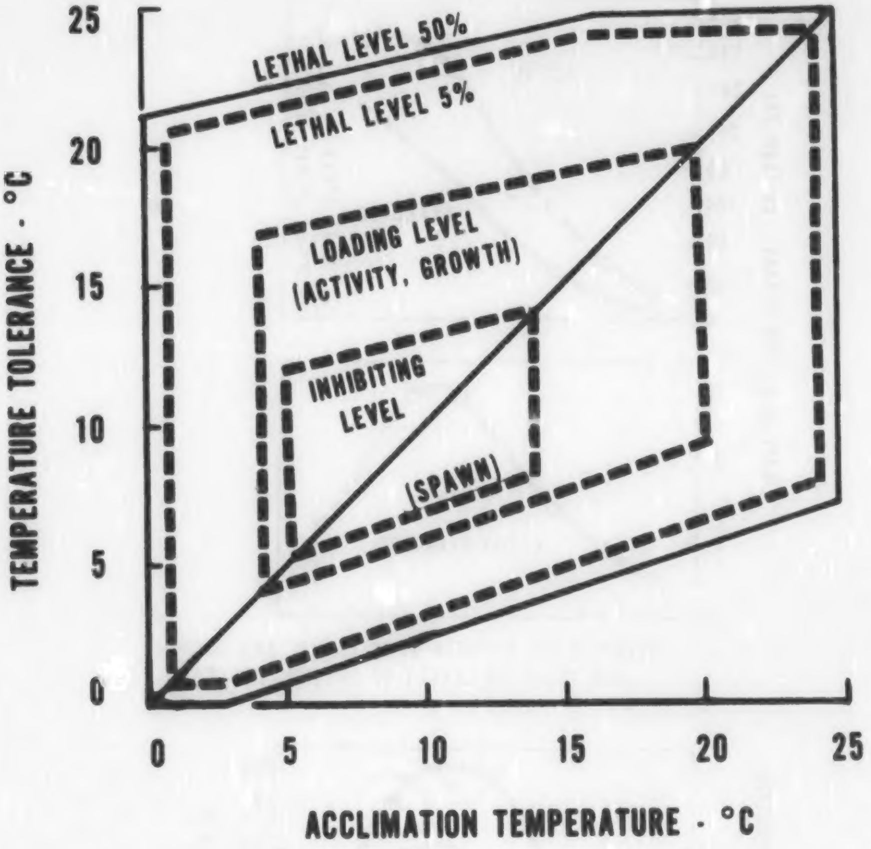
MEDIAN RESISTANCE TIMES FOR FISH ACCLIMATED TO 20°C

FIGURE 4



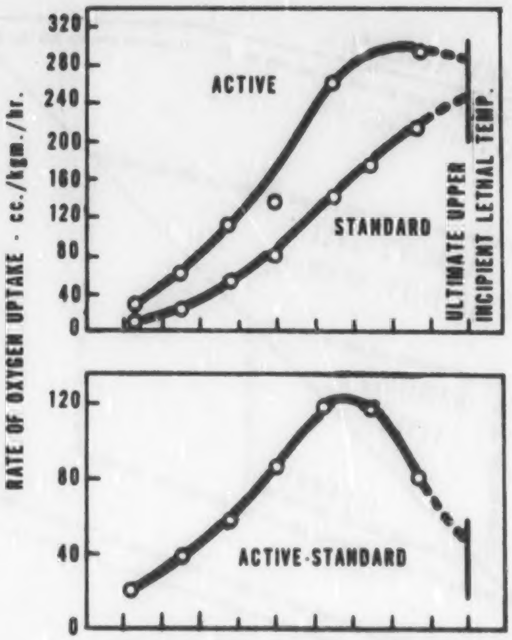
EFFECT OF ACCLIMATIZATION TEMPERATURE ON UPPER
LETHAL LIMIT OF SPECKLED TROUT

FIGURE 5



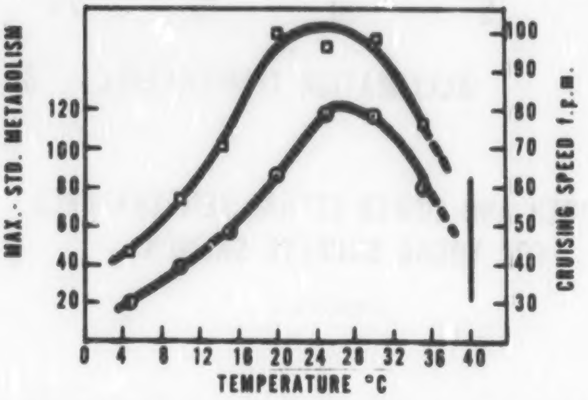
UPPER AND LOWER LETHAL TEMPERATURES
FOR YOUNG SOCKEYE SALMON

FIGURE 6



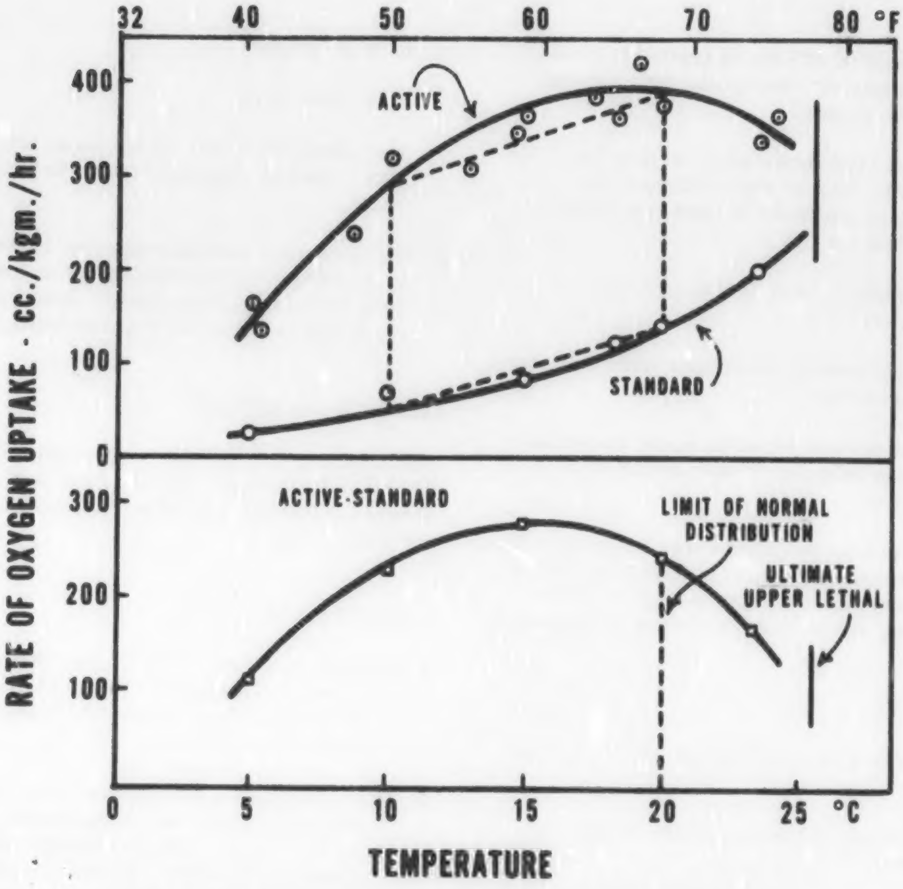
RELATIONSHIP BETWEEN TEMPERATURE AND ACTIVE AND STANDARD LEVELS OF OXYGEN UPTAKE

FIGURE 7



DIFFERENCE BETWEEN MAXIMUM AND STANDARD LEVELS OF OXYGEN UPTAKE (LOWER CURVE) AND SPEED AT WHICH GOLDFISH CAN SWIM STEADILY AT VARIOUS TEMPERATURES

FIGURE 8



RELATION OF OXYGEN UPTAKE TO TEMPERATURE IN ACCLIMATED SPECKLED TROUT

FIGURE 9

1 The difference between active metabolic rate and standard rate is called the scope of activity (Graham, 1949).

2 Figure 8 demonstrates the similarity between the graphs of cruising speed of gold fish versus temperature and scope of activity versus temperature.

V DECREASED RESISTANCE TO TOXIC SUBSTANCES

A Although literature on fish toxicology is voluminous and excellent, summaries of published data are available (Doudoroff, 1957).

1 The specific effects of temperature on the toxicity of many pollutants are not well documented.

2 DeSylva (1969) has summarized the available data on the combined and synergistic effects of heat and toxic materials on fish.

B Two conclusions can be drawn from existing data.

1 Toxicity usually increases with increased temperatures.

2 Specimens subjected to toxic materials are less tolerant of temperature extremes.

C Since chemical reaction rates increase with increased temperatures and metabolic rates generally increase at higher temperatures, these results should be expected.

VI SUMMARY

The Effects of Elevated Temperatures on the Biota are:

A A shift in population structure of the ecosystem.

B Heated effluents, causing stress on the community, cause a reduction in the number of species with an increase in numbers of individuals per species.

C Lethal temperatures are affected by many variables.

D Those variables which are considered as major factors are acclimation, exposure time, and the species being observed.

E Sublethal temperatures can act as:

1 A catalyst

2 A depressant

3 An activator

4 A restrictor

5 A stimulator

6 A controller

F Temperature is one of the most important water quality characteristics to life in water.

G Temperature can increase the toxic action of pollutants by increasing the metabolic rate of the organism and by speeding the chemical reaction of the pollutants.

ACKNOWLEDGMENT:

Material for this outline was taken from Thermal Pollution: Status of the Art, Frank L. Parker and Peter A. Krenkel, authors.

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This outline prepared by John F. Wooley, Biologist, Manpower & Training Branch, Pacific Northwest Water Laboratory, FWQA.

PHYSICAL AND CHEMICAL EFFECTS OF WATER TEMPERATURE

I INTRODUCTION

A With but a few exceptions, the physical and chemical effects of temperature change on water quality are more subtle than, or subordinate to, the more direct and dramatic biological effects. The important direct effects, moreover, usually are not significant in themselves to water use, but, rather, as they affect in secondary or tertiary sequence some other water property or phenomena.

B The more important primary and secondary effects are:

1 Density on stratification and density currents, and the whole array of impacts stratification and density currents have on water quality and its management.

2 Density and viscosity on sediment transport and the array of impacts this sediment transport mechanism has on movement and deposition of particulate matter.

3 Vapor pressure on evaporation rate and its impact on cooling processes and water loss.

4 Partial pressure of gases on gas solubility (particularly oxygen) and its impact on reaeration.

5 Microbial reaction rate on deoxygenation by organic matter and its impact on the oxygen sag.

II PHYSICAL EFFECTS OF WATER TEMPERATURE

A Temperature affects many physical properties of water. Of these, the most significant to water quality are density, viscosity, vapor pressure and solubility of dissolved gases. Table 1 shows the effect of incremental changes in temperature on these properties for fresh water.

B Very slight differences in density are sufficient to cause thermal stratification in quiescent water bodies, but stratification stability also depends on water movement and depth.

1 While the stratification process in reservoirs and lakes is well known, the resulting changes in water quality are not. The changes are becoming increasingly important because of the growth of complex water resource systems.

2 At the end of a winter season, the impounded water is usually of a fairly uniform quality and has a relatively low temperature. At the onset of higher atmospheric temperatures, the surface water and the incoming water temperatures are raised and this lighter water tends to "float" on the colder and denser water already in the lake.

3 Three definite strata may be formed, the surface stratum or epilimnion, the lower stratum or hypolimnion, and a transition zone called the thermocline, where the maximum rate of change of temperature with depth occurs.

4 Stratification may exist until autumn, when the lake begins to lose heat more quickly than it is absorbed. As the water becomes cooler and more dense, the thermocline sinks, unstable conditions occur and the reservoir mixes or overturns. In climates where the water temperature goes below 4° C, two turnovers may occur per year.

5 Many impounded waters circulate completely but some circulate only partially, these lakes being called meromictic by limnologists. This stable, lower layer can be caused by either an accumulation of dissolved or suspended solids in the water and may render this lower portion of the lake unsuitable for a water supply.

TABLE 1

WATER PROPERTIES

Temperature (°C)	Temperature (°F)	Density (gm/cm^3)	Abs. Viscosity (centipoises)	Pressure (mm Hg)	Dissolved Oxygen Saturation (mg/l)
0	32	0.99987	1.7921	4.58	14.6
4	39.2	1.00000			
5	41	0.99999	1.5188	6.54	12.8
10	50	0.99973	1.3077	9.21	11.3
15	59	0.99913	1.1404	12.8	10.2
20	68	0.99823	1.0050	17.5	9.2
25	77	0.99707	0.8937	23.8	8.4
30	86	0.99567	0.8007	31.8	7.6
35	95	0.99406	0.7225	42.2	7.1
40	104	0.99224	0.6560	55.3	6.6

6 Stable stratification is common in lakes and reservoirs where there is a specific gravity difference of about .001 or .002 between waters of the upper layer (epilimnion) and lower layer (hypolimnion). Such stratification inhibits vertical mixing and oxygen transfer to lower waters.

7 In stratified reservoirs, cool, incoming waters may travel almost directly to the dam outlet in a density current at a depth of compatible specific gravity. This reservoir characteristic is important in predetermining release temperatures and in selecting optimum discharge elevation.

C Water temperature affects velocity and sediment transport through changes in density and viscosity.

1 Stokes' law describes the velocity of settling particles in a non-turbulent medium according to the following equation.

$$V = \frac{d^2 g}{18} (\rho_s - \rho_w)$$

where V = settling velocity, cm/sec

ρ_s = density of settling particle, gm/cm^3

ρ_w = density of water, gm/cm^3

μ = viscosity of liquid, poises

d = diameter of particle, cm

g = acceleration of gravity = 980 cm/sec^2

As indicated, settling velocity is inversely proportional to the water viscosity and density.

2 Both properties contribute to increased settling rates at elevated temperatures. These increased settling rates may promote better water treatment plant operation, though probably to no measurable degree.

3 A difference in settling velocities can have a significant effect on the location and amount of sediment and sludge deposition in sluggish rivers, reservoirs and estuaries.

D Evaporation rate increases as water temperature rises and elevates water vapor pressure.

1 Evaporation is caused by the wind and the difference in water vapor pressure between the air and the water. Since vapor pressure is a driving force in evaporation, an increase in temperature will cause an increase in evaporation, assuming other factors to be constant.

2 Evaporation is one of the key mechanisms in cooling water bodies.

E Water temperature affects gas solubility and its resultant impact on reaeration.

1 Most living organisms depend on oxygen in one form or another to maintain their life and reproductive processes; thus an adequate supply of oxygen must be available for any healthy aquatic environment. Hence, the relation of water temperature to gas solubility is a very important aspect of thermal pollution.

2 Oxygen does not react chemically with water. Therefore, its solubility is directly proportional to its partial pressure at any given temperature under equilibrium conditions with the atmosphere. The effect of temperature on the solubility of oxygen in fresh water under one atmosphere of pressure is shown in Table 1.

3 Temperature changes cause complicated adjustments in the dynamic oxygen balance in waters and compound the difficulty of relating dissolved oxygen and other factors to oxygen demand, atmospheric reaeration, photosynthetic production, diffusion, mixing, etc. General temperature rises, which decrease the oxygen holding capacity, may limit oxygen quantities which are already less than optimum.

4 Atmospheric nitrogen, with a solubility about one-half that of oxygen, is usually not considered an important control parameter for water quality. However, recent evidence on the Columbia River indicates that fish may be seriously affected in waters which have become super-saturated with nitrogen through rapid warming or pressure reduction after dam discharge.

III CHEMICAL EFFECTS OF WATER TEMPERATURE

A Many factors affect chemical reactions, including the nature and concentration of reacting substances, catalytic influence and temperature. The last named is important because chemical changes speed up as the temperature rises. In general, the speed of a chemical change is approximately doubled for each 10° C (18° F) rise in temperature.

B In an irreversible reaction, higher temperatures will decrease the time required to produce the final products. In a reversible reaction, the process is complete when the reactants reach a point of dynamic stability, i.e., when the rate of forward reaction equals the rate of reverse reaction. In this case, temperature influences both the length of time required to reach equilibrium and the proportion of reactants and products at equilibrium conditions.

C Most of the chemical effects on water quality, which are influenced by temperature, center around microbial activity. Any chemical reaction or change that results from a life process is properly termed a biochemical reaction.

1 The majority of chemical reactions that organisms bring about occur through catalytic action at far lower temperatures than would be needed in the absence of catalysts. Such catalysts are known as enzymes, and are themselves temperature-sensitive.

2 The rate of microbial activity increases, to a point, with the rates of chemical reactions. The majority of organisms affecting chemical water quality are in the mesophylic classification and thrive in a temperature range of 10 to 40° C (18 to 104° F). For this group, activity usually reaches a maximum between 30 and 37° C (86 and 99° F), then falls off as enzymes become less active.

D Temperature affects not only the rate at which a reaction occurs, but the extent to which the reaction occurs, but the extent to which the reaction takes place.

1 When considering temperature changes in a receiving water, one must contemplate changes in ionic strength, conductivity, dissociation, solubility and corrosion.

2 With an increase in temperature, these changes might very well result in differing chemical requirements in the water treatment plant.

E Taste and odor problems induced by temperature-accelerated chemical or biochemical action are accentuated when oxygen is depleted.

1 Substances which may accumulate include hydrogen sulfide, sulfur dioxide, methane, partially oxidized organic matter, iron compounds, carbonates, sulfates, and phenols.

2 In addition to greater amounts of accumulating substances, tastes and odors are usually more noticeable in warmer water due to decreased solubility of gases.

F Biodegradable organic material entering water exerts a biochemical oxygen demand (BOD) which must be satisfied before assimilation of the material is completed.

1 When the temperature of a receiving water rises, the intensified action of microorganisms causes the BOD to be satisfied in a shorter distance from the discharge than would be accomplished at a lower temperature. Figure 1 depicts oxygen sag curves for a stream in which all conditions, i.e., streamflow, wasteflow, BOD of the waste, and initial percent DO saturation, were held constant, except temperature.

It is apparent from the curves that the deoxygenation effect caused by waste assimilation is exerted over a shorter stream distance at higher temperatures; also that oxygen depletion occurs to a greater extent, since the sag point is lower at elevated temperature. Hence, it is possible that the discharge of an organic waste that previously had not caused excessive oxygen depletion could pose problems at an elevated temperature.

G Chemical effects of slightly increased temperatures may have minor beneficial influences on water treatment.

1 Disinfectant action is generally more rapid at higher temperatures. For example, for a given dose of free chlorine, the period required to disinfect water at 46°F is more than nine times greater than at 104°F.

2 Reports on coagulant dosages are contradictory, although reports indicate a savings of 30 to 50¢ per million gallons per each 10°F rise in temperature.

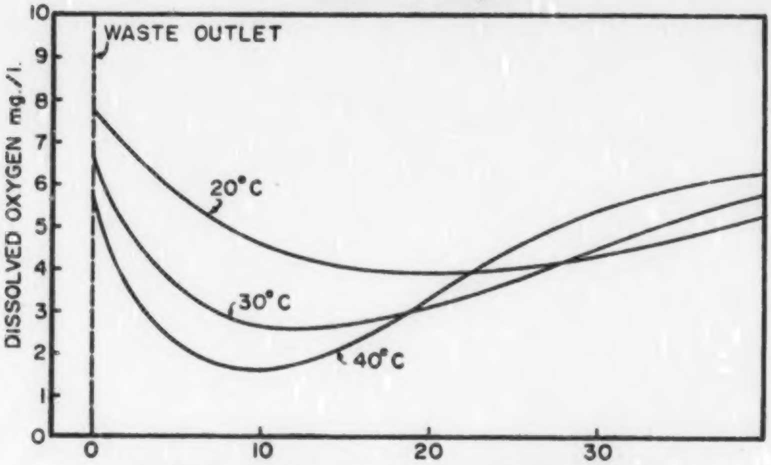
3 The potential beneficial effects must be weighed against the undesirable effects such as induced slime or algae growth, taste and odor problems, or unpalatable drinking water temperatures.

IV SUMMARY

A The physical and chemical effects of temperature change on water quality usually are not significant in themselves to water use but rather as they affect in secondary or tertiary sequence some other water property or phenomenon.

FIGURE 1

RELATION BETWEEN TEMPERATURE AND OXYGEN PROFILE
(After La Berge)



Miles from Outlet Discharging Organic Waste

B The more important effects relate to:

1 Stratification and density currents
2 Sediment transport and deposition
3 Evaporation
4 Saturation with gases
5 Microbial activity
6 Taste and odor
7 Deoxygenation and reaeration

ACKNOWLEDGMENT:

Material for this outline was taken from "Thermal Pollution: Status of the Art," by Frank L. Parker and Peter A. Krenkel and "Industrial Waste Guide on Thermal Pollution," FWPCA, September 1968 (revised).

This outline was prepared by D. S. May, Former Microbiologist, Manpower and Training, PNWL, Corvallis, OR.

EFFECTS OF THERMAL POLLUTION ON MICROORGANISMS

I INTRODUCTION

When considering the effect of temperature changes on bacteria, it is important to distinguish between rapid changes, which may induce thermal shock, and slow, gradual changes. Organisms can adapt to gradual changes in the environment; however, such adaptation may take several life cycles, i.e., each successive generation is better adapted to its environment. Since bacteria have very short life cycles, many generations may occur within a relatively short time. If a gradual temperature increase occurs over several life cycles, then each successive generation is subjected to only a small portion of this total temperature increase. Thus, bacteria can adapt to slow temperature changes more easily than higher forms such as fish.

II TEMPERATURE RELATIONSHIPS AND GROWTH

A The relationships of temperature to microorganism growth and survival are very complex. Bacteria can be grouped according to their temperature requirements for growth:

20° C (68° F) - psychrophiles

20 to 55-65° C (68 to 131-149° F) - mesophiles

55-65° C (131-149° F) - thermophiles

1 The majority of bacteria are mesophilic. Many found in natural waters are saprophytes, i.e., organisms that live on preformed organic matter, which have optimum temperatures of 22 to 28° C (70 to 82° F).

2 Parasitic bacteria have optimum temperatures near 37° C (98.6° F) and include those microorganisms pathogenic to man. Changes in temperature have a large effect on these organisms' rate of activity.

B In general, the higher the temperature, the more active a microorganism becomes, unless the temperature or a secondary effect becomes a limiting factor.

1 Metabolic activity of thermophilic organisms is much greater at their optimum than psychrophilic organisms at their optimum. Examination of the known effects of temperature on waste treatment processes demonstrates the validity of this statement.

2 A distinct difference exists between the ability of a microorganism to endure a given temperature and its ability to grow well under identical conditions.

C The effect of temperature on bacteria cannot always be considered separately from other environmental factors. Some species are more abundant in winter, while others abound in the summer when different environmental conditions are encountered.

D Rising stream temperatures can be favorable for those bacteria which multiply in water by inducing the recurring cycles of life and death more rapidly.

1 Higher temperatures in an organically polluted stream generally result in increased bacterial numbers, and low temperatures are not conducive to rapid growth.

2 Temperatures of 1 to 8° C (33.8 to 46.4° F) may suppress growth and multiplication, but bacteria persist longer at these cool temperatures.

E Increases in bacterial populations are not necessarily harmful.

1 Those bacteria which play an active role in stream self-purification do perform a useful function. These

include the bacteria which aerobically oxidize organic material, as well as those responsible for nitrification and anaerobic decomposition of bottom sediments.

2 Increases in pathogenic bacteria always pose a problem when domestic wastes are present.

F Bacterial slimes cause unsightly scums and foul fishing nets. Rivers carrying a high organic load often develop such deleterious slime growths at low temperatures.

1 A study on the Columbia River indicated that Sphaerotilus slime grows best at 10 to 15°C (50 to 59°F). Growth ceases below 4°C (39.2°F).

2 Infestation of Sphaerotilus may occur below 10°C (50°F), given sufficient time. Beds of Sphaerotilus slime extend farther downstream from a waste outfall during the winter than in the summer, because warmer temperatures may inhibit the organism's food conversion efficiency, or because of competition for food from other microorganisms.

III EFFECT OF TEMPERATURE ON POLLUTION INDICATOR ORGANISMS

A The organism of particular interest to water quality management is E. coli, as it is the prime indicator of fecal pollution. It is shown in Figure 1 that increased temperatures may lead to optimum growth conditions for this organism in receiving waters.

B Recent studies on the survival of bacterial indicators of pollution showed that, the lower the temperature, the longer the survival. Table 1 shows the average time for 99% reduction in original titers of microorganisms from three sources.

IV SUMMARY

In summary, the temperature of natural waters, even during the summer, is usually below the optimum for pollution-associated bacteria. Increasing the water temperature increases the bacterial multiplication rate when the environment is favorable and the food supply is abundant. Increasing temperature within the growth range causes a more rapid die-off when the food supply is limited.

ACKNOWLEDGMENT:

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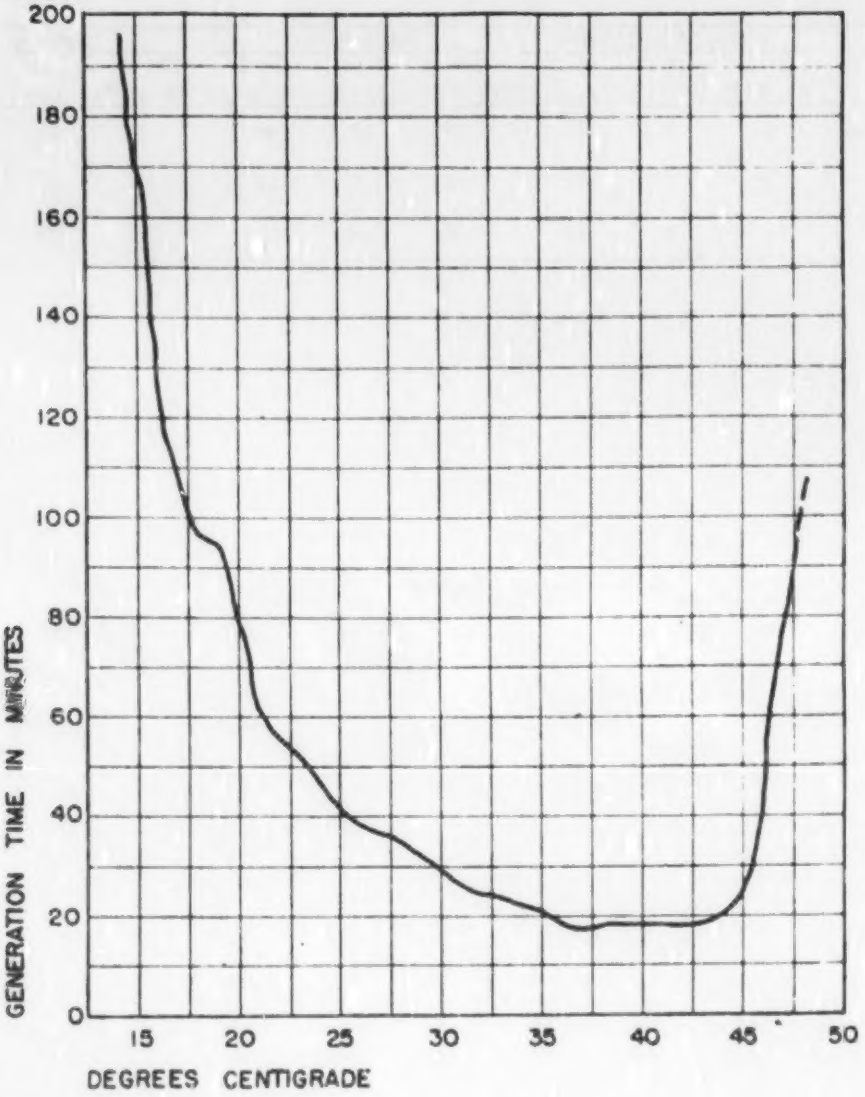


FIGURE 1
GROWTH RATE OF E. COLI

TABLE 1

AVERAGE TIME IN DAYS FOR 99.9% REDUCTION IN ORIGINAL TITER OF MICROORGANISMS AT THREE TEMPERATURES FROM THREE SOURCES

	Little Miami River			Ohio River			Sewage		
	28° C (82.4° F)	20° C (68° F)	4° C (39.2° F)	28° C (82.4° F)	20° C (68° F)	4° C (39.2° F)	28° C (82.4° F)	20° C (68° F)	4° C (39.2° F)
A. aerogenes	6	8	15	15	18	44	10	21	56
E. coli	6	7	10	5	5	11	12	20	48
S. fecalis	6	8	17	9	18	57	14	26	48

EFFECTS OF THERMAL POLLUTION ON PRIMARY PRODUCERS

I INTRODUCTION

In any system we must take into account the primary producers which make the sun's energy available to the zooplankton, fish, etc., and, finally to us. Generally, in these northern latitudes, we think of temperature increases as being beneficial in that they tend to increase production. In some cases, this may be an advantage but all production is not necessarily good. Eutrophication is a problem as important as thermal pollution and just as complex. It may be accelerated by the addition of heat.

II PRIMARY PRODUCERS

A Algae

  1 Blue-greens

  2 Pigmented flagellates

  3 Nonmotile green

  4 Diatoms

B Aquatic Macrophytes

C Periphyton (bottom algae)

  1 Means "around plants."

  2 Aufwuch's is equivalent to the term periphyton.

III BLUE-GREEN ALGAE

A What are the blue-green algae?

  1 Microscopic algae

  2 Has no nucleus of chloroplast

  3 Has blue pigment as well as green

B Where are they found?

  1 Free floating in water

  2 Attached to rocks, wood or other substrates

C When are they most common?

  1 Always found in plankton sample

  2 The proportion of blue-greens to other algae depends on the time of the year and the chemical composition of the water. The blue-greens usually occur in abundance only during the warm months of the year (late summer and early fall).

D Of what importance are the blue-green algae?

  1 They have both positive and negative economic significance.

    a First link in food chain

    b Some are nitrogen fixers

    c Cause taste and odor problems

    d Filter cloggers

IV PIGMENTED FLAGELLATES

A What are the flagellates

  1 Free swimming

  2 Well organized nucleus and plastids

  3 Have whip like flagellum

B Where are they found?

  1 Free swimming in water

  2 Resting stage found on bottom not attached

C When are they most common?

  1 Always found year around

  2 Predominate in late spring and early fall

D Of what importance are the pigmented flagellates

  1 Cause taste and odor

  2 Clog filters

V NONMOTILE GREEN ALGAE

A What are the nonmotile greens?

1 Filamentous forms

2 Called pond silk, green felt, frog-spawn algae, and stoneworts (common names).

B Where are they found?

1 Attached to a substrate

2 Some are free floating

C When are they most common?

1 Found all year

2 Predominate in early summer

D Of what importance are the nonmotile green algae?

1 Filter clogging

2 Taste and odor

3 Cause unsightly growths

4 Produce slime which interferes with some industrial uses of water such as paper manufacture and cooling towers.

VI DIATOMS

A What are the diatoms?

1 Cells of very rigid form

2 Have brown pigment besides green

3 Cell walls have ornamented patterns

B Where are they found?

1 Free swimming (planktonic)

2 Attached to a substrate

C When are they most common?

1 Found year around

2 Predominate in early spring and late fall and winter

D Of what importance are the diatoms?

1 Taste and odor

2 Filter clogging

VII PERIODICITY OF FRESHWATER ALGAE

A Diatoms - early spring, late fall and winter

B Pigmented flagellates - late spring and early fall

C Nonmotile greens - early summer

D Blue-greens - late summer and early fall

VIII TOLERANCE OF ALGAE TO NATURAL HEAT

A Diatoms are quite intolerant to increased temperatures.

B The pigmented flagellates and nonmotile greens are moderately tolerant to increased temperatures.

C Blue-greens are very tolerant to increases in temperature.

IX RANGES OF OPTIMUM PRODUCTION

A Cairns of Virginia Polytechnic Institute (1956 - Effects of Increased Temperature on Aquatic Organisms. Industrial Wastes 1(4):(150-152) has given the following optimum ranges for primary producers in an unpolluted stream (Figure 1).

1 Diatoms - 18-20°C (64.4-68°F)

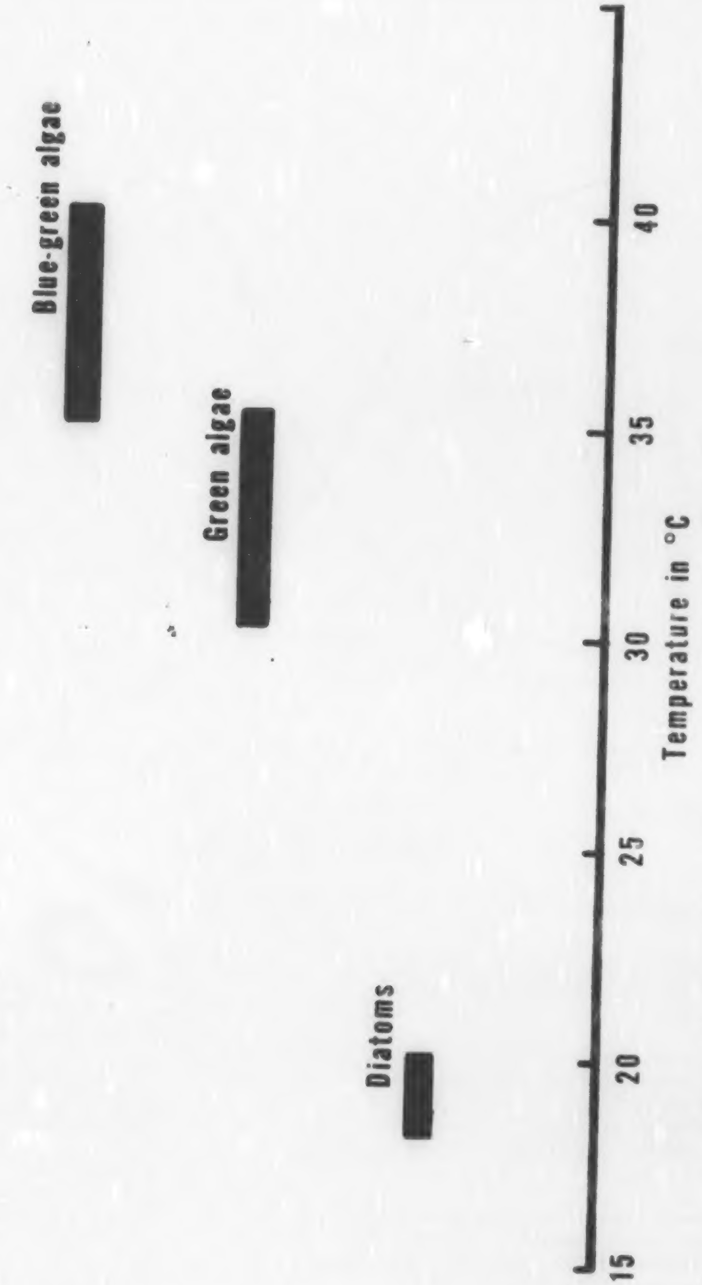
2 Green algae - 30-35°C (86-95°F)

3 Blue-green algae - 35-40°C (95-104°F)

B The effect of temperature on population structure can best be illustrated with a mixed algal population which is subjected to a gradual increase in temperature. Figure 2 demonstrates the shift in predominance from diatoms at 20°C to blue green algae, the species often found in abundance under conditions of organic or chemical pollution, in the range of 35 to 40°C (Cairns, 1956).

C These temperatures may be too high but they do illustrate the point. From this we see that addition of heat may cause a shift in the type of organisms in abundance in any body of water. This could be especially important if the shift is from green to a noxious blue-green algae. A shift in algal types accompanied by an increase in growth rates could cause severe problems in water used for recreation or domestic water supplies.

OPTIMUM TEMPERATURE RANGES FOR PRIMARY PRODUCERS IN AN UNPOLLUTED STREAM



From Cairns, Effects of Increased Temperatures On Aquatic Organisms. Industrial Wastes. 1 (4): 150-152

FIGURE 1

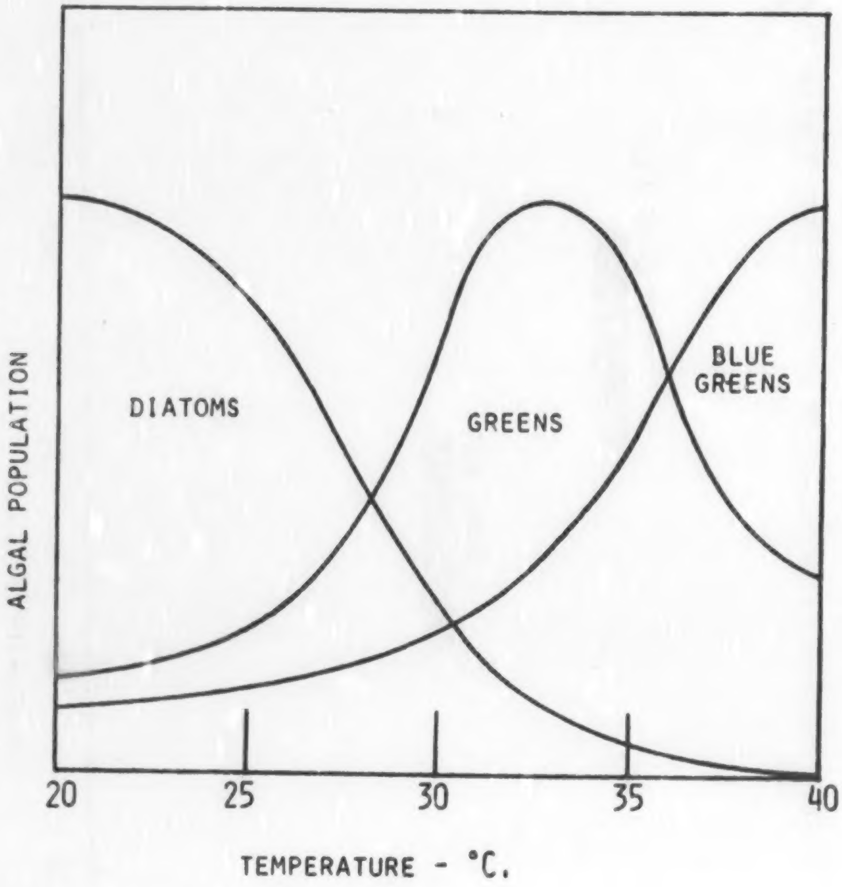


Figure 2. ALGAE POPULATION SHIFTS WITH CHANGE IN TEMPERATURE

X POPULATION SHIFTS OF AQUATIC MACROPHYTES CAUSED BY HEAT ADDITION

A In some areas beds of larger aquatic plants (aquatic macrophytes) may become a problem when they clog waterways and interfere with beneficial uses such as boating and fishing or when they clog water intakes.

1 We could expect increases in these plants with increases in temperature and increased light penetration if there is less wash load with the higher temperature.

2 We could expect shifts in species composition if conditions become more favorable to warm water forms.

B Anderson, of the American University, detected such a change around the Chalk Point steam electric plant on the Patuxent River estuary, and here it was undesirable.

1 There were extensive beds of Widgeon grass, Ruppia, in the vicinity of the outfall and on the other side of the river. It was later found that any temperature over 20°C inhibits new growth from the Ruppia stolon so when the power plant went in and produced a temperature of 35°C at the outlet there was little or no new vegetative growth and Ruppia was replaced by a species of Potamogeton.

2 This was important to the area because the Ruppia was used as food by some 30 species of ducks and birds but the species of Potamogeton which replaced it has very little food value.

C Some work like this is now being done to determine effects of heat on other primary producers but much still needs to be done. The whole problem is extremely complex and effects of temperature increase are often difficult to separate from eutrophication.

XI EFFECTS UPON PERIPHYTON

A Trembley (1960) chose the periphyton as a group of organisms showing promise as an indicator of the effects of heated discharges. Periphyton is a collective name for all those attached aquatic plants and animals when solid surfaces are exposed to natural waters.

B To follow changes in periphyton populations of the river, Trembley used a so-called Pralgometer, which is simply a device for suspending microscope slides in the stream.

1 Only one point in each river transect was sampled.

2 Stream organisms attach to the glass slides, even grow, within a few days.

3 Differences in counts (species and individuals) above and below the source of heated water should indicate the effect of the heat upon the population.

C Trembley concluded that the periphyton was considerably altered by the power plant discharge. Return to normal conditions occurred by 4,500 feet downstream.

XII SUMMARY

We need to know a great deal more about thermal effects on aquatic organisms to really predict the effects on our environment but enough is already known about many organisms to allow us to take some positive measures in avoiding thermal effects.

ACKNOWLEDGMENT

Material for this outline was taken from the technical seminar paper "Biological Effects," Dr. Ronald Garton, author.

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This outline was prepared by John F. Wooley, Biologist, Manpower and Training Branch, Pacific Northwest Water Laboratory, FWQA.

EFFECTS OF THERMAL POLLUTION ON THE BENTHOS

I INTRODUCTION

A Fish may be obviously important but they are not the only important organisms or the only ones being studied at present. The food organisms are just as important in the long run. Lose the organisms which convert the energy of the primary producers to a form usable by the fish and we lose the fish themselves.

B In a river, most of the microscopic population are benthic organisms, since the plankton have difficulty maintaining position in the stream flow. The benthos is a stationary community which should reflect the action of the temperature in the area of influence. Of course, bottom debris may serve to protect benthic organisms to some extent from full exposure to the heated water.

II SUBLETHAL EFFECTS ON AQUATIC INSECTS

A In most western streams the stoneflies, caddisflies and mayflies are the primary fish food organisms. At the same time, these organisms have definite environmental requirements and cold, well-oxygenated water is a prime factor.

1 Preliminary work at the Duluth Laboratory indicates that temperatures would probably become lethal to any cold water fish like trout before the insects would die.

a According to Usinger (1956), the heat tolerance of macroscopic invertebrates is well above that of fish.

b For example, soldier fly (stratiomyidae) larvae were found living in thermal waters at temperatures up to 120°F.

2 Table 1 shows 96 hour TL_m values determined for some insect species by Nebeker and Lemke of the Duluth Laboratory.

a These temperatures are well above the 12°C suggested as the maximum limit for spawning and egg development in salmon and trout.

b This doesn't tell the whole story because the insects may be harmed in other ways.

B Gaufin, formerly of Utah, and also Nebeker of the Duluth Laboratory, have demonstrated that temperature increases can cause premature emergence.

1 A 10°C rise from ambient winter temperature caused one species of stonefly to emerge in January instead of May. "One must imagine how perplexed these organisms must be as they expect nice warm spring weather only to freeze to death as they emerge."

2 Nebeker found that a temperature increase for another species caused the males to emerge as much as two months ahead of the females!

C Either situation would prevent reproduction and would be fatal to the species although not fatal to individuals prior to emergence.

D Even without lethal effects we may find changes in community due to variation in optimum temperatures between species. This has not been studied enough in the field to really determine the overall effect on a natural system but it is something which we will have to know more about in the future.

III SUBLETHAL EFFECTS ON SHELLFISH

A Most shellfish, such as clams, oysters, crabs and lobsters, which are directly beneficial to man as a food source, are marine, stenothermal organisms. Some species are stenothermal for one developmental stage and eurythermal for another. Generally, however, breeding and spawning requirements are stenothermal.

1 The time of mollusc, e.g. clams, oyster, etc., spawning is temperature dependent.

2 Most molluscs with specific temperature breeding relationships spawn in the spring and summer, and many do not spawn until a certain temperature is reached.

B The American oyster Crassostrea virginica spawns at temperatures between 15 and 34°C

TABLE 1

Temperatures at which 50% of the test species died after 96 hours exposure (TL_m^{96}) when acclimated at 10°C for one week.

Species Tested	TL_m^{96} (°Celcius)
Taeniopteryx maura (winter stonefly)	21°
Ephemerella subvaria (mayfly)	21.5°
Isogenus frontalis (stonefly)	22.5°
Allocapnia granulata (winter stonefly)	23°
Stenonema tripunctatum (mayfly)	25.5°
Brachycentrus americanus (caddisfly)	29°
Pteronarcys dorsata (stonefly)	29.5°
Acroneuria lycorias (stonefly)	30°
Paragnetina media (stonefly)	30.5°
Atherix variegata (true fly)	32°
Boyeria vinosa (dragonfly)	32.5°
Ophiogomphus rupinsulensis (dragonfly)	33°

12°C (55°F) Maximum temperature recommended in Water Quality Criteria for spawning and egg development of salmon and trout

From: Nebeker, Alan V. and Armond E. Lemke, 1968. Preliminary studies on the tolerance of aquatic insects in heated waters. Journal of Kansas Entomological Society 41: 413-418. July, 1968.

(59 and 93.2°F) depending on its condition, and spawning is usually triggered by a rise in temperature.

C Many species tolerate temperatures in excess of those at which breeding occurs.

  1 For example, the shore crab *Carcinus maenas* thrives, but does not breed, at temperatures of 14 to 28°C (57.2 to 82.4°F).

  2 In this case, temperature limits the population, but migration of organisms can occur from outside the heated area.

D Physiology, metabolism and development are all affected by temperature.

  1 The American oyster *C. virginica* ceases feeding at temperatures below 7°C (44.6°F).

    a Above 32°C (89.6°F) ciliary activity, which is responsible for water movement, is decreased.

    b At 42°C (107.6°F) almost all body functions cease, or are reduced to a minimum.

  2 The European oyster *Ostrea lurida* tends to close its shell as temperatures drop.

    a At 4 to 6°C (39.2 to 42.8°F) the oyster's shell remains closed most of the time.

    b At 6 to 8°C (42.8 to 46.4°F) the shell opens for about 6 hours per day.

    c At 15°C (59°F) the shell stays open for 23 hours a day.

E Very little is known about prolonged effects of temperatures above 32 to 34°C (90 to 94°F) on oysters; however, long exposure to such temperatures may impede the oyster's normal rate of water circulation. When either low or high temperatures cause shells to close or ciliary action to cease, oysters cannot feed and subsequently lose weight. Thus, temperature changes can produce an effect similar to chronic toxicity.

F The distribution of benthic organisms is temperature dependent.

  1 The American oyster *C. virginica* is present in Gulf Coast waters that may vary between 4 and 34°C (39.2 and 93.2°F), but the European oyster *O. edulis* is restricted to water temperatures of 0 to 20°C (32 to 68°F).

  2 The opossum shrimp *Neomysis americana* is not often found at temperatures above 31°C (87.8°F) in the Chesapeake estuary.

IV LETHAL EFFECTS

A Studies of particular species of benthic macroinvertebrates have indicated that lethal temperatures vary considerably with the type of organism.

  1 Laboratory investigations on the freshwater snail *Lymnaea stagnalis* showed a lethal temperature of 30.5°C (89.6°F), while the species *Viviparous malleatus* did not succumb until the temperature reached 37.5°C (99.5°F).

  2 Agerborg (1932) observed a freshwater snail, *Physa gyrina*, living and reproducing nicely in zones up to 91.4°F in heated wastewater.

  3 Hutchinson (1947) reported that *Viviparous malleatus*, a freshwater snail, was not killed until the temperature reached 37.5°C (99°F).

B Several snails, including *Australorbis glabratus*, suffered heat damage at 105.8°F (Von Brand, et. al. 1948).

C Other examples show that the limpet, *Ancylus fluviatilus*, was not hurt by a temperature of 96.8°F while 87.8°F was lethal to *Acrolexus lacustris* (Berg, 1952).

D When an unidentified species of crayfish was acclimated to 45°F, it had a lethal temperature of 93°F (Trembly 1961).

E Sprague (1963) reported a 24-hour lethal temperature of 94.3°F for a freshwater sowbug, *Asellus intermedius*, and a scud, *Gammarus fasciatus*. Another scud, *Hyalella azteca*, was killed at 91.8°F.

F Field work on rivers has indicated that benthic organisms decrease in number when water temperature exceeds 30°C (86°F).

  1 The macroinvertebrate riffle fauna of the Delaware River has decreased due to heated water discharges.

a At 35°C (95°F) many caddisfly, Hydropsyche, were dead, and those which remained alive were extremely sluggish.

b This study suggests that there is an upper tolerance level near 32.2°C (90°F) for a variety of different benthic forms with extensive losses in numbers and diversity accompanying a further increase in temperature.

V POPULATION SHIFTS CAUSED BY HEAT ADDITION

A Trembley (1960) studied the bottom fauna of the Delaware River at the Martins Creek Power Plant.

1 In the zone of maximum temperature rise rise just below the outfall, there was obvious reduction of species and individuals.

2 In the cool water unaffected by the thermal overflow, there was no reduction in macroinvertebrates.

3 During the cooler seasons there was repopulation of the areas affected during the hot months by thermal discharge.

4 Even during the summer, there was a significantly higher standing crop at the downstream site in comparison to the normal river control station.

B Coutant (1962) followed Trembley's Martins Creek research with a study of the macroinvertebrate bottom fauna of the riffle areas of Big Kaypush and Little Kaypush Rapids.

1 He confirmed Trembley's conclusions. From July through October, there was substantial reduction in the number, diversity, and biomass of benthic organisms in the path of the heated water.

2 At a distance of one mile downstream from the point of discharge, he found a normal population structure.

3 In his traverse studies, he observed an increase in both variety and number of organisms as he progressed from hot to cool water, demonstrating the effect of temperature as the primary limiting factor.

4 The work also showed the restricted effect of heated discharges in changing the biological communities. The data suggest a tolerance limit near 90°F for a normal population structure with extensive loss in numbers and diversity of organisms accompanying further rise.

C Wurtz and Dolan (1960) reported a study on bottom organisms in the Schuylkill River at the Cromby Power Plant.

1 These authors gave no temperature data; however, the subcommittee of the Pennsylvania Electric Association (Mason, 1962) showed severe temperature alteration in this reach of river since the plant used 85% of the river flow as cooling water.

2 The river showed a very elevated temperature and slow recovery. Wurtz and Dolan evaluated the effects of heated discharges in terms of biological depression, biological distortion, and biological skewness.

3 Station 10 at Phoenixville Pumping Station, 0.5 miles below the plant, showed the greatest deviation.

4 At Station 13, six miles below the power plant, the river biology had recovered. This case illustrates ultimate recovery from an extreme condition.

VI SUMMARY

It is clear from the valid biological data presented that increased temperature of the water does alter the species and individual composition of the benthic population which, of course, being generally sessile, is unable to avoid exposure.

ACKNOWLEDGMENTS

Material for this outline was taken from The Industrial Waste Guide, Bruce A. Tichenor and Alden G. Christianson, authors; Thermal Pollution: Status of the Art, Frank L. Parker and Peter A. Krenkel, authors; and Technical Seminar Paper, Biological Effects, Dr. Ronald Garton, author.

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This outline was prepared by John F. Wooley, Biologist, Manpower and Training Branch, Pacific Northwest Water Laboratory, Federal Water Quality Administration.

EFFECTS OF THERMAL POLLUTION ON FISH LIFE

I INTRODUCTION

A The physiology of fishes is directly affected by temperature.

1 Fishes are classed as Poikilothermic animals, i.e., their body temperatures follow changes in environmental temperatures rapidly and precisely.

2 In such animals, the factors favoring heat loss tend to equal the factors producing body heat, and thus the body approaches environmental temperatures.

3 In a majority of fishes, the body temperature differs by only 0.5 to 1.0° C (0.9 to 1.8° F) from that of the surrounding water.

4 A fundamental requirement of fishes is that the external temperature be well suited to internal tissue functionality.

B The single most important point in analyzing or predicting the effects of temperature change on a fishery is to look at the individual species important to the specific water body under study.

II GENERAL

A Metabolism--Rates of metabolism and activity increase with increasing temperature.

1 According to Van't Hoff's law, metabolic activity can double or even triple over a 10° C (18° F) rise in temperature.

2 This increase in metabolic rate and activity will occur over most of the tolerated temperature range and then often cease suddenly near the upper lethal temperature.

3 The rates of increased activity vary with different species, metabolic processes, and temperature ranges or levels.

4 The rates may also be modified by salinity and oxygen factors.

5 Changes in metabolic rates caused by temperature changes may be signaling factors for spawning or migration.

6 Chemical reactions within the fish's body cells may be accelerated by temperature increases.

7 Temperature induced changes in cell chemistry are associated with four possible death mechanisms.

a Enzyme inactivity caused by the acceleration of the enzyme reaction to such a state that the enzyme is no longer effective.

b The coagulation of cell proteins.

c The melting of cell fats.

d The reduction in the permeability of cell membranes.

8 Cells may also be killed by the toxic action of the products of metabolism.

B Reproduction - the temperature range within which many fishes reproduce is narrower than that required by the majority of functions.

1 Fishes generally spawn when a certain temperature level is reached. Of course, this level varies from species to species.

2 Some fish spawn on a drop in temperature, while others respond to a rise in temperature.

3 Even though the temperature requirements for breeding are narrow, fishes may populate a heated area by continued migration from the outside.

C Development - temperature changes affect fish development in several ways.

1 Abnormal temperatures can affect embryonic development.

2 Low temperatures may slow down development, but in some cases, fish attain a larger final size because of their slow, long continued growth rather than the rapid growth experienced at higher temperatures.

D Distribution - temperature is one of the more important factors governing the occurrence and behavior of fish life; it affects the general location of a given species and may also modify the species composition of a community or an ecosystem.

1 Tropical and subtropical fishes are more stenothermal than those found in fresh water.

2 Some cold water stenothermal forms may be eliminated by heated discharges, while the effect on some eurythermal (tolerant of a wide temperature range) species may be to increase the population.

3 In tropical areas, species live close to their upper thermal limits, thus the effect of a thermal discharge can be quite severe.

4 In northern areas, species may live in temperatures as much as 16°C (28.8°F) below their upper lethal temperature and will not be as severely affected.

5 Laboratory tests have shown that a slow rate of decrease in environmental temperature is more important for maintaining life than a slow rate of increase.

6 Lethal cold can be more important than lethal heat as a factor limiting the distribution of marine fish and as a hazard to some in their native habitats.

E Synergistic Action - synergism is defined as the simultaneous action of separate agents which together, have a greater total effect than the sum of their individual effects.

1 In reference to water temperatures, synergistic action refers to the fact that temperature rises increase the lethal effect of toxic substances to fish and may also increase the susceptibility of the fish to many diseases.

2 A 10°C (18°F) rise in temperature doubles the toxic effect of potassium cyanide, and an 8°C (14.4°F) rise triples the toxic effect of o-xylene.

3 The temperature effect on toxicity varies with each substance and with concentrations of any specific material; no hard and quick rule may be formulated to determine this temperature effect.

4 Since domestic and industrial wastes are numerous in our nation's waters, the synergistic action between temperature and toxicity is a relatively common occurrence.

a Fish kills have accompanied small temperature rises which might have been relatively harmless in an unpolluted stream free of toxic substances.

b The concentration of a substance may be harmless at one temperature but may contribute to fish mortalities when combined with the stress imposed by higher temperatures.

5 The virulence of fish pathogens may be increased by higher temperatures.

a The myxobacteria Chondrococcus columnaris, which can cause death through tissue destruction, becomes more virulent as temperature is increased.

F Dissolved Oxygen - two factors associated with rising water temperature are decreases in available oxygen and increases in metabolic rates.

1 These factors combine to render the aquatic environment less compatible to fish life at higher water temperatures.

2 At low water temperatures in the range of 0 to 4°C (32 to 39.2°F) a dissolved oxygen level of 1 to 2 mg/l is sufficient for survival of many freshwater fish species. When the temperature reaches 15 to 20°C (59 to 68°F), less than 3 mg/l of dissolved oxygen is often lethal.

3 At these temperatures, oxygen levels as high as 5 mg/l are sometimes required to support normal activity beyond that of merely staying alive.

G Acclimation - the temperature to which fish become adjusted over an extended period of time, i.e., the thermal history, is important because of its influence on lethal temperature levels.

1 The capacity to acclimate depends on the genetic background, environmental history, physiological conditions, and age of the organism involved.

a The resistance of animals to cold is much more variable than resistance to heat.

b The resistance to cold varies with size, smaller fish resisting best.

2 Acclimation to different temperatures may involve changes in orientation, migration, and other behavioral aspects such as territorialism and biological rhythms.

a Gradual temperature changes are tolerated much better than rapid changes.

b Brief or intermittent exposure to high temperature can result in markedly increased resistance to heat which is not readily lost on subsequent exposure to low temperature.

c It is the rapid onset of low temperatures that probably causes death, outstripping the ability of fish to acclimate and resulting in greater mortality.

d Deaths resulting from the inability of fish to rapidly acclimate to lowering temperatures have been reported.

3 Acclimation to low temperature usually tends to shift the lower thermal limit downward, and acclimation to high temperatures tends to shift the upper limits upward.

a The ability to acclimate affects the temperature range that a fish can tolerate.

b Fish acclimated to cold winter temperatures are often subjected to lethal temperatures in the spring as warmer water is encountered.

III FRESHWATER FISHES

A Maximum Temperatures - maximum temperatures have been determined for numerous species of freshwater fish.

1 These temperatures indicate the highest temperature at which a fish can survive, but they are often higher than the maximum temperature at which a species can survive for long periods.

2 Maintaining water temperature at these maximums does not insure the maintenance of a fish population.

3 Table 1 shows maximum and minimum temperatures for various species and acclimation temperatures.

a Values shown are LD_{50} temperatures, i.e. temperature survived by 50% of the test animals.

b These figures are based on specific test conditions, so care must be taken in interpreting the data.

TABLE 1

MINIMUM AND MAXIMUM TEMPERATURES FOR CERTAIN FRESHWATER FISHES

Fish	Acclimated To		Minimum Temperature*			Maximum Temperature*		
	°C	°F	°C	°F	Time, Hr.	°C	°F	Time, Hr.
Bass, largemouth	20.0	68.0	5.0	41.0	24	32.0	89.6	72
	30.0	86.0	11.0	51.8	24	34.0	93.2	72
Bluegill (*Lepomis macrochirus purpurescens*)	15.0	59.0	3.0	37.4	24	31.0	87.8	60
	30.0	86.0	11.0	51.8	24	34.0	93.2	60
Catfish, channel	15.0	59.0	0.0	32.0	24	30.0	86.0	24
	25.0	77.0	6.0	42.8	24	34.0	93.2	24
Perch, yellow	5.0	41.0	---	---	--	21.0	69.8	96
(winter)	25.0	77.0	4.0	39.2	24	30.0	86.0	96
(summer)	25.0	77.0	9.0	48.2	24	32.0	89.6	96
Shad, gizzard	25.0	77.0	11.0	51.8	24	34.0	93.2	48
	35.0	95.0	20.0	68.0	24	37.0	98.6	48
Shiner, common (*Notropis cornutus frontalis*)	5.0	41.0	---	---	--	27.0	80.6	133
	25.0	77.0	4.0	39.2	24	31.0	87.8	133
	30.0	86.0	8.0	46.4	24	31.0	87.8	133
Trout, brook	3.0	37.4	---	---	--	23.0	73.4	133
	20.0	68.0	---	---	--	25.0	77.0	133

*Values are LD_{50} temperature tolerance limits, i.e., water temperatures survived by 50 percent of the test fish.

c Temperature limits for a given species will vary slightly depending on the fish's rate of heating, size, and physiological condition.

4 A temperature need not kill a fish directly for it to be lethal.

a Brook trout were found to be comparatively slow in catching food minnows at 17.2°C (63°F) and virtually incapable of catching minnows at 21°C (70°F).

b Even though their lethal limit is 23 to 25°C (73.4 to 77°F) the fish could not survive in this temperature due to a lack of food (Table 1).

B Preferred Temperatures - most biologists agree that fish can live for short periods in waters of abnormally high temperatures, but at these high temperatures the fish cannot perpetuate their population.

1 Fish seek out the temperature that is best suited for their survival.

2 This "preferred temperature" is given in Table 2 for several species of yearling fish based upon laboratory experiments.

3 Table 3 shows the temperature at which fish in the natural environment seem to congregate, thus indicating their "preferred temperature."

TABLE 2

THE FINAL PREFERRED TEMPERATURE FOR VARIOUS SPECIES OF FISH AS DETERMINED BY LABORATORY EXPERIMENTS

Species	Final Preferred Temperature °C	°F	Authority
Bass, largemouth	30.0-32.0	86.0-89.6	Fry, 1950
Bass, smallmouth	28.0	82.4	Fry, 1950
Bluegill	32.3	90.1	Fry & Pearson, 1952
Carp	32.0	89.6	Pitt, Garside & Hepburn, 1956
Muskellunge	24.0	75.2	Jackson & Price, 1949
Perch, yellow	24.2	75.6	Ferguson, 1958
Perch, yellow	21.0	69.8	McCracken & Starkma, 1948
Trout, brook	14.0-16.0	57.2-60.8	Graham, 1948
Trout, brown	12.4-17.6	54.3-63.7	Tait, 1958
Trout, lake	12.0	53.6	McCauley & Tait, 1956
Trout, rainbow	13.6	56.5	Garside & Tait, 1958

4 The level of thermal acclimation influences the range of temperatures preferred.

In general, the difference between the acclimation temperature and the preferred temperature decreases as the acclimation temperature increases.

5 Competition between species is also important to distribution and survival since different species have different species have different preferred temperatures.

Temperatures higher than optimum may not kill trout, but they may produce environmental conditions favorable for the production of coarse fish and reduce the trout's food supply.

IV MARINE, ESTUARINE, AND ANADROMOUS FISHES

A Spawning - limits of temperature requirements for spawning are usually much more stringent than for adult fish survival.

1 The normal spawning temperature for sockeye salmon is between 7.2 and 12.8° C (45-55° F); lower and upper lethal limits are 0° C (32° F) and about 25° C (77° F), respectively.

2 Pink salmon spawn best near 10° C (50° F).

3 During migration salmon do not feed, so high water temperatures which increase their metabolic rate may result in fuel depletion before spawning can occur.

TABLE 3

PREFERRED TEMPERATURES FOR VARIOUS SPECIES OF FRESHWATER FISH BASED ON FIELD OBSERVATIONS

Species	Preferred Temperature		Water Body	Location	Authority
	°C	°F			
Alewife	4.4- 8.8	39.9-47.8	Cayuga Lake	New York	Galligan, 1951
Bass, largemouth	26.6-27.7	80.0-81.9	Norris Res.	Tennessee	Dendy, 1948
Bass, rock	14.7-21.3	58.5-70.3	Lakes	Wisconsin	Hile & Juday, 1941
" "	20.7	69.3	Streams	S. Ontario	Hallam, 1958
Bass, smallmouth	20.3-21.3	68.5-70.3	Nebish Lake	Wisconsin	Hile & Juday, 1941
" "	21.4	70.5	Streams	S. Ontario	Hallam, 1958
Bass, spotted	23.5-24.4	74.1-75.9	Norris Res.	Tennessee	Dendy
Perch, yellow (small)	12.2	54.0	Muskellunge Lake	Wisconsin	Hile & Juday, 1941
Perch, yellow (large)	20.2-21.0	68.4-69.8	Lakes	Wisconsin	Hile & Juday, 1941
Shad, gizzard	22.5-23.0	72.5-73.4	Norris Res.	Tennessee	Dendy
Trout, brook	14.2-20.3	57.6-68.5	Moosehead Lake	Maine	Cooper & Fuller
" "	15.7	60.3	Streams	S. Ontario	Hallam, 1958
" "	12.0-20.0	53.6-68.0	Redrock Lake	Ontario	Baldwin, 1948
Trout, lake	10.0-15.0	50.0-59.0	Cayuga Lake	New York	Galligan, 1951
" "	14.0	57.2	White Lake	Ontario	Kennedy, 1941
" "	11.0-11.5	51.8-52.7	Moosehead Lake	Maine	Cooper & Fuller, 1945
" "	8.0-10.0	46.4-50.0	Louisa & Redrock Lakes	Ontario	Martin, 1952
Walleye	20.6	69.1	Trout Lake	Wisconsin	Hile & Juday, 1941
"	22.7-23.2	72.9-73.8	Norris Res.	Tennessee	Dendy, 1948

4 Fish migration is hampered by unfavorable temperature conditions.

5 A thermal block of 21.1°C (70°F) at the mouth of the Okanogan River, Washington, prevented migration into the stream from the Columbia River.

6 Generally for salmon, upstream migration and reproduction occur best at temperatures between 7.2 and 15.6°C (45 and 60°F).

B Eggs - the incubation of eggs and development of fry generally have more critical temperature requirements than either fingerling or adult fish.

1 Table 4 shows the minimum and maximum temperatures reported for the successful hatching of various species of marine, estuarine, and anadromous fish eggs.

2 Care must be taken not to equate successful hatching with fry survival; Chinook salmon eggs incubated at 16.1°C (61°F) hatched successfully, but suffered severe mortality in the late fry stage.

C Young Fish - Table 5 shows the temperature limits for the survival of various species of young marine, estuarine, and anadromous fishes at several acclimation temperatures.

1 This information is based on laboratory tests which often produce data not directly transferable to the natural environment.

2 Laboratory tests on striped bass fingerlings showed an upper lethal temperature of 35°C (95°F), but studies in the Atlantic Ocean indicated striped bass fish kills occurring at temperatures of 25 to 27°C (77.0 to 80.6°F).

3 Fish in the estuarine environment are more susceptible to temperature changes than those in fresh water. However, wider ranges of tolerance between species exist in estuarine waters.

4 Decreases in temperature seem to have more of an effect on estuarine fishes than on freshwater fishes.

TABLE 4

TEMPERATURE RANGES FOR SUCCESSFUL EGG HATCHING OF VARIOUS MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Lower Limit		Upper Limit		Authority
	°C	°F	°C	°F	
Bass, striped	12.8	55.0	23.9	75.0	Albercht, 1964
California killifish	16.6	61.9	28.5	83.1	Hubbs, 1965
California grunion	14.8	58.6	26.8	80.1	Hubbs, 1965
Salmon, Chinook	5.8	42.4	14.2	57.6	Combs & Burrows, 1957
	9.4	48.9	14.4	57.9	Seymour, 1956
	5.6	42.1	14.4	57.9	Leitritz, 1962
Salmon, sockeye	4.4-5.8	39.9-42.4	12.8-14.2	55.0-57.6	Combs, 1965
Sea lamprey	15.0	59.0	25.0	77.0	McCauley, 1963
	15.6	60.1	21.1	70.0	Piavis, 1961

TABLE 5
LETHAL TEMPERATURE RANGES FOR YOUNG MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Acclimation Temperature		Lower Lethal Temperature		Upper Lethal Temperature		Authority
	°C	°F	°C	°F	°C	°F	
Greenfish	12.0-28.0	53.6-82.4	4.1-13.0	39.2-55.4	28.7-31.5	83.7-88.7	Doudoroff, 1942
Herring	7.5-15.5	45.5-59.9	-1.8 to -0.75	28.8-30.7	22.0-24.0	71.6-75.2	Blaxter, 1960
Salmon, Chinook	5	41	----	----	21.5	70.7	Brett, 1956
" "	10	50	0.8	33.4	24.1	75.7	" "
" "	15	59	2.5	36.5	25.0	77.0	" "
" "	20	68	4.5	40.1	25.1	77.2	" "
" "	23	73.4	7.4	45.3	----	----	Brett, 1952
" "	--	----	----	----	26.7	80.0	Kerr, 1953
Salmon, chum	5	41	----	----	21.8	71.2	Brett, 1956
" "	10	50	0.5	32.9	22.6	72.7	" "
" "	15	59	4.7	40.5	23.1	73.6	" "
" "	20	68	6.5	43.7	23.7	74.7	" "
" "	23	73.4	7.3	45.2	----	----	Brett, 1952
Salmon, pink	5	41	----	----	21.3	70.3	Brett. 1956
" "	10	50	----	----	22.5	72.5	" "
" "	15	59	----	----	23.1	73.6	" "
" "	20	68	----	----	23.9	75.0	" "
Salmon, silver	5	41	0.2	32.4	22.9	73.2	Brett, 1956
" "	10	50	1.8	35.1	23.7	74.7	" "
" "	15	59	3.5	38.3	24.1	75.7	" "
" "	20	68	4.5	40.1	25.0	77.0	" "
" "	23	73.4	6.4	43.5	----	----	Brett, 1952
Salmon, sockeye	5	41	0.0	32.0	22.2	72.0	Brett, 1956
" "	10	50	3.1	37.6	23.4	74.1	" "
" "	15	59	4.1	39.4	24.4	75.9	" "
" "	20	68	4.7	40.5	24.8	76.6	" "
" "	23	73.4	6.7	44.1	----	----	Brett, 1952
Topsmelt	20	68	10.1	50.2	31.8	89.2	Doudoroff, 1942

a In studies of young greenfish to determine the resistance and acclimation of marine fishes to temperature changes, Doudoroff found that heat resistance was gained rapidly and lost slowly.

b Acclimation to decreasing temperatures was slower than acclimation to increasing temperatures.

c Transposed to the practical case, this fact implies that the shutdown of a power generating plant may be more detrimental than its normal discharge of heat.

5 Anadromous fingerlings have maximum growth in the temperature range of 10 to 15.6° C (50 to 60° F).

6 Research on the effects of temperature on swimming speed indicates that for young sockeye salmon optimum cruising speed occurred at 15° C (59° F), and for young silver salmon at 20° C (68° F); thus, the fish's mobility for protection and feeding is affected by temperature changes.

D Adult Fish - Table 6 shows the lethal temperature limits for several species of adult marine, estuarine, and anadromous fishes.

1 Adult fish are usually able to select their preferred temperatures, unless trapped in shallow water or forced to migrate through thermal blocks.

TABLE 6

LETHAL TEMPERATURE LIMITS FOR ADULT MARINE, ESTUARINE, AND ANADROMOUS FISHES

Species	Acclimation Temperature °C	°F	Lower Lethal Temperature °C	°F	Upper Lethal Temperature °C	°F	Authority
Alewife	---	---	---	---	26.7-32.2	80.0-90.0	Trembley, 1960
Bass, striped	---	---	6.0- 7.5	42.8-45.5	25.0-27.0	77.0-80.0	Talbot, 1966
California killifish	14.0-28.0	57.2-82.4	---	---	32.3-36.5	90.1-97.7	Doudoroff, 1942
Common silverside	7.0-28.0	44.6-82.4	1.5- 8.7	34.8-47.8	22.5-32.5	73.3-90.3	Hoff & Westman, 1966
Flounder, winter	21.0-28.0	69.8-82.4	1.0- 5.4	33.8-41.6	---	---	" " "
" "	7.0-28.0	44.6-82.4	---	---	22.0-29.0	71.6-84.2	" " "
Herring	---	---	-1.0	30.2	19.5-21.2	67.1-70.1	Brawn, 1960
Northern swellfish	14.0-28.0	57.2-82.4	8.4-13.0	47.1-55.4	---	---	Hoff & Westman, 1966
" "	10.0-28.0	50.0-82.4	---	---	28.2-33.0	82.9-90.4	" " "
Perch, white	4.4	40.0	---	---	27.8	82.0	Trembley, 1960
Salmon (general)	---	---	0.0	32.0	26.7	80.0	Columbia Basin Inter-agency Comm., 1966

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THERMAL ACCLIMATION OF AQUATIC ORGANISMS

I INTRODUCTION

A The upper limit of heat tolerance range is not an unalterably fixed point.

B Organisms can be trained to live at higher temperatures (up to a certain limit) by intermittent or gradual exposure to higher temperatures than those in the environment in which they live.

1 This training process is called acclimation or acclimatization.

2 Bullock (1955) has reviewed the subject of physiological compensation for temperature changes in the poikilotherms.

3 Young animals are more easily acclimated than mature animals (Shelford, 1929).

4 Acclimation can last for some time after return of the organism to an environment of a lower temperature.

II HISTORY OF TEMPERATURE ACCLIMATION

A Temperature acclimation of animals has been known for many years.

1 Davenport and Castle (1895) acclimated toad tadpoles to 24-25°C for four weeks while controls were held at 15°C.

2 The temperature necessary to produce heat rigor was 3.2°C higher in the acclimated organisms.

3 Loeb and Wasteneys (1912) studied the time requirements to hold Fundulus at 27°C in order to render the fish "immune" to sudden transfer to 35°C.

a All fish held at 27°C for 44 hours survived.

b Fish held for only 21 hours suffered some mortality.

c These workers also learned that acclimation does not require continuous exposure.

III LABORATORY ACCLIMATION

A Fry, et al. (1942) found that the upper lethal temperature of goldfish could be raised to 41°C by increasing the acclimation temperature to the limit, 36.5°C.

B Iezzi, et al. (1952) was able to acclimate the following fish species to higher lethal temperatures: Bluegill sunfish (Lepomis macrochirus macrochirus), brown trout (Salmo fario), bluntnose minnow (Hyborhynchus notatus), brown bullhead (Ictalurus nebulosus), and fathead minnow (Pimephales promelas).

C Black (1953) found that the black bullhead (Ictalurus melas melas) and (Cyprinus carpio) could be acclimated to higher temperatures.

D Many other fishes were investigated and most could be acclimated.

IV METHODS OF ACCLIMATION

A Different methods of acclimation have been tried.

1 Fry, et. al. (1946) acclimated young speckled trout (Salvelinus fontinalis) at a rate of 1°C rise per day, a method which they felt might serve for all types of fish.

2 Cocking (1959) said that 1/20°C per hour rise (1.2°C per day) until the desired temperature was reached gave complete acclimation.

B Before stocking rainbow trout in lower Nashotah Lake in southeastern Wisconsin, Threinen (1958) acclimated the fish in the following way:

1 The fish were placed in a tank truck containing the same spring water in which the fish had been living. The temperature was 51°F.

2 The truck was allowed to stand in the sun from 9:00 a.m. until 6:00 p.m. when the temperature reached 63°F.

3 The next morning sufficient warm water was added to increase the temperature to 65°F.

4 The fish were then put into the tank which had a surface temperature of 73°F.

5 No mortality was observed.

V NATURAL ACCLIMATION

A Acclimation of organisms occurs in their natural habitat with seasonal temperature changes.

1 Hathaway (1928) found that the gradual natural rise in stream temperature in the spring raised the upper lethal level for five fish species.

2 The species were: yellow perch, largemouth bass, bluegill, pumpkin seed and toad tadpoles.

B Brett (1944) determined the upper lethal temperature for a number of fish in Canadian lakes.

1 The upper lethal temperature rose with increasing lake temperatures.

2 Species studies were: bullhead, golden shiner, creek chub, fathead minnow, redbelly dace and finescale dace.

C Trembley (1960) described an interesting case of natural acclimation which developed in a week.

1 On May 7, he observed a school of alewives trapped in the lagoon.

2 This lagoon had a temperature gradient from 80°F to 90°F.

3 All fish were milling about in the 80°F water.

4 When his movements frightened the alewives into the hotter water, many died of heat shock.

5 On May 14, the lagoon had warmed to a gradient of 83°F - 92°F.

6 Fish were swimming 83°F water which was lethal one week earlier.

VI SUMMARY

A Organisms can be acclimated to live at temperatures higher than those they have been living in.

B Many fish species were investigated in laboratory experiments and most could be acclimated.

C Acclimation of organisms occurs in their natural habitat with seasonal temperature changes.

D It has been noted by several observers that acclimated fish lost this acclimation very slowly.

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THE INFLUENCE OF TEMPERATURE ON BEHAVIOR OF FISH

I INTRODUCTION

Observations of heated water discharges have indicated that fish tend to move toward them in colder months and to move away during summer months. This is an example of temperature selection by motile organisms.

A Organisms move toward some preferred temperature.

B This is also temperature avoidance, since the organism is migrating away from an undesirable temperature.

C This phenomenon of temperature selection then is a type of protective response.

II TEMPERATURE PREFERENCE

A Doudoroff (1938) reported that Girella nigricans and other marine fish showed selection of temperatures which were high in comparison to their environment.

The fish tended to avoid areas of rapid temperature change.

B Silliman (1943) found that the vertical distribution of eggs and larvae of the pilchard (Sardinops caerulca) was correlated with the vertical temperature gradient of the water.

C Examples of species of fish showing temperature selection were large mouth bass (Fowler, 1940), young Pacific salmon (Brett, 1952), carp (Pitt, et al, 1956), roach (Alabaster and Downing, 1958), rainbow trout (Garside and Tait, 1959, and Threinen, 1958), young sturgeon Dyzan, 1962), and golden shiner (Trembley, 1960).

D Dryer and Benson (1957) described operations at the New Johnsonville Steam Plant. Water for condenser cooling is drawn from Kentucky Lake and the spent water, raised in temperature 10° F, is released into a rectangular discharge harbor from which it eventually flows back into the lake.

1 Tremendous numbers of shad were observed in the harbor during the winter months.

2 The shad became rare after March 15 when the temperatures approached 60° F.

3 Blue catfish, channel catfish and bluegill then concentrated in the harbor.

4 The catfish left the harbor when the temperature exceeded 80° F.

III AVOIDANCE OF HIGH TEMPERATURES

A Mantleman (1960) found that very young fish reacted most quickly in avoiding undesirable temperatures.

B Alabaster (1963) described field observations which indicated that larger fish move away from heated effluents.

1 Fish clearly avoided certain high temperatures.

2 Trout and bleak seldom swam into water warmer than 20° C.

3 Grayling and tench never went into water warmer than 18 or 26° C, respectively.

C Slow rates of temperature increase cause no movement of fish.

D An increase from 6° C to 9° C very suddenly drove fish away.

E The data on temperature selection (or avoidance) indicates that fish will not remain in a potentially harmful environment.

1 Fish will move toward a more favorable situation if an escape route is available.

2 The majority of fish, given the opportunity, successfully avoid lethal temperatures.

IV SUMMARY

A Most fish will avoid lethal temperatures in the environment if escape routes are available.

B Unfortunately, during some of the critical life stages, i.e., egg and fry development, the organisms are capable of little or no motility, thus they are subjected to all environmental conditions in their immediate area.

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EFFECTS OF TEMPERATURE ON REPRODUCTION AND GROWTH

I INTRODUCTION

What are some of the significant effects of temperature on fish and fish food organisms? The importance of reproduction in maintaining a population of organisms need not be emphasized. Fishermen are well aware of the spawning seasons for fish. The bass fisherman knows that the largemouth bass is in shallow water guarding its nest in the spring and this is a good time to take the fish. Most angling seasons are set up to protest fish during the spawning seasons.

II REPRODUCTION

A Studies on the natural history of fish give more information on the relationship of spawning season to water temperature.

  1 Largemouth bass in Minnesota begin spawning activity in the spring when water temperatures reach 15° C (Kramer and Smith, 1962).

  2 In Alabama, largemouth bass have been observed to spawn at temperatures from 20-24° C (Swingle, 1956).

  3 Such studies only tell us what temperatures fish can spawn at, but don't give any valid or precise temperature which must not be exceeded for an extended period during the spawning season.

B Work at the National Water Quality Laboratory includes determination of the thermal requirements for reproduction of several fish species.

  1 Brook trout exposed continuously to various constant temperatures for five months spawned successfully at 10° C.

  2 There was 50% reduction in spawning success at 13° C, and very little spawning or hatching occurred at 16° C.

  3 At 19° C fish appeared to be sexually mature but they did not spawn.

  4 At 21° C males were sterilized and in the female the eggs never became ripe and soon were resorbed.

C In other species such as the yellow perch, temperature has a greater influence on the rate of development of the gametes.

  1 Perch exposed to 16° C spawned one month earlier than fish exposed to 4-8° C.

  2 At excessive temperatures, eggs of sexually mature females were aborted, (unpublished data, NWQL).

D When fish are exposed to warm water for long periods, maturation can be inhibited as observed for the four-spined stickleback (Merriman and Schedl, 1941).

  1 The maturation process should be thought of as a growth process whereby the food reserves are being channeled into the egg as well as into fish flesh.

  2 It was concluded for this species that normal maturation of the eggs requires temperatures below a certain threshold.

  3 The function of low temperature is to slow down the metabolism and activity of the fish so the normal increase in yolk-content of the egg can be processed, as it does in nature.

  4 At high temperatures, more food reserves are required and greater amounts of potential yolk material is used for combustion for energetic sources.

E Once the eggs have been deposited, another portion of the year is devoted to their successful development.

1 The major effect of temperature is on the rate of development.

2 Brook trout eggs hatch in 45 days at 10° C and 90 days at 5° C.

3 At abnormally high and low temperatures, the rate constant changes which corresponds to a reduction in the hatchability of the eggs and an increase in deformities.

F Development in short can be regarded as a chain of reactions linked in sequence (Hayes, et al, 1953).

1 These chains branch and the effect of temperature is to encourage some of the branches more than others.

2 The result of abnormal temperatures is to accelerate some branches out of phase of the others which produces disorganization and deformed fry.

G There is considerable difference in maximum incubation temperatures for several fish species.

1 For whitefish, the maximum temperature for normal hatch was 4° C (Price, 1940), for brook trout 12° C (Embody, 1934), for northern pike 18° C (Lillelund, 1966), and for largemouth bass 24° C (Kelly, 1968).

2 A difference of 3-6° C may mean a highly successful hatch and not hatch.

III GROWTH

A Another important parameter in the production of desirable aquatic organisms is good growth rates.

1 Fast growing fish and big fish are important to fishermen, but statistics tell me that only 10% of the fishermen want quality fishing; most only want fish to catch.

2 Faster growing fish generally mature at an earlier age and produce a greater total weight of eggs than slower growing fish of the same size (McFadden, et al, 1965).

B Bluegills and bass in southern states may spawn after 1 year's growth (Swingle and Smith, 1950), but don't reach sexual maturity until 2-3 years in northern states (Lagler, 1956; Reigier, 1963).

These differences result primarily from differences in the length of the growing season.

C The size of young fish has been demonstrated to influence their survival.

1 In a laboratory experiment, over winter mortality of young smallmouth bass was greater among small fish (MacLeod, 1967).

2 Field observations on migrating sockeye salmon smolts indicated that smaller fish were more vulnerable to predation (Forester, 1954).

D In general, high growth and reproductive rates impart a natural resiliency to the population enabling it to withstand pressures from predation and exploitation.

E Growth rates increase with increase in temperature up to an optimum temperature and then begin to decrease.

1 Growth should be considered the net result of temperature acting on several other variables simultaneously; these are the appetite or food consumption, activity, and basal metabolic rate which influences the amount of food required to maintain body weight.

2 At high water temperatures, it becomes extremely difficult to increase in weight when activity and food consumption decreases and the food requirements increases with the basal metabolic rate.

F In the absence of adequate nutrition, higher temperatures will accelerate loss of weight (Wohlschlag and Juliano, 1959). Low water temperature is the only means these organisms have to slow down their basal metabolism and conserve their energy reserves.

G Examination of the growth rates of several larval fishes at various temperatures has shown that the temperature for maximum growth is less than 3° C from their lethal temperatures.

1 Optimum temperature for growth was 27° C and deformities were induced in 14 days at 30° C.

2 These deformities were not reversible, however; mortality decreased when removed to lower temperatures.

3 The margin of safety between maximum growth and lethal temperature is very slim for several larval fishes.

IV SUMMARY

The temperature requirements for reproduction are more restrictive than for growth and activity which is again more restrictive than lethal conditions. Fish apparently prefer temperatures near optimum conditions which is manifested through their behavior. This same philosophy holds for most aquatic animals, but has been worked out in more detail for fish. It is quite apparent that no single item will characterize a species as a cold- or warm-water organism. Their entire physiological makeup has adapted to their environment. Another point to emphasize is that no single number will protect any given species throughout the entire year. These organisms have evolved in an environment that undergoes regular seasonal changes in temperature. As a consequence, the thermal requirements for reproduction is much lower than for growth and activity. It follows that higher temperatures would not only be permissible, but desirable during a portion of the year to allow for good growth rates.

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This outline was prepared by John F. Wooley, Biologist, Manpower & Training Branch, Pacific Northwest Water Laboratory, FWQA.

TEMPERATURE REQUIREMENTS OF CENTRARCHIDS

I INTRODUCTION

The family Centrarchidae includes many of the so-called pan fishes. It is safe to say that in North America there is a Centrarachid for every type of water warmer than that suitable for trout.

II DIFFERENCE BETWEEN A COLD- AND WARM-WATER FISH

A Table 1 compares the difference between a cold-water fish, the brook trout, and a warm-water fish, the largemouth bass.

B Table 1 illustrates that temperature requirements for reproduction are more restrictive than for growth and activity which is again more restrictive than lethal conditions.

C It is quite apparent from these results that no single item will characterize a species as a cold-or-warm-water organism.

D The organism's entire physiological make-up has adapted to their environment.

III SPAWNING HABITS AND TEMPERATURE

A Largemouth, smallmouth, and spotted bass have been reared in hatchery ponds for many years; thus a good deal of information is available on spawning habits as related to temperature.

1 Lamkin stated, when the water reached 56° F (13.3° C), largemouth bass began nest building.

2 Spawning did not take place, however, until the waters were about 66° F (18.9° C).

3 The spawning temperature of the spotted bass is 64° F (17.8° C), as observed by Howland.

4 Thus, spotted bass spawn at temperatures about 2° F lower than the largemouth bass and 2° F higher than the smallmouth bass.

5 The spawning temperature of the smallmouth bass is about 62° F (16.7° C) as observed by Troutman. This 4° F or more lower than that of the largemouth bass.

TABLE 1

	Temperature (° C)			
Item	Brook Trout	Citation	Largemouth Bass	Citation
Max. egg development	10° - 12°	(Embody, 1934)	24° - 27°	(Kelly, 1968)
Optimum Growth	13° - 16°	(Baldwin, 1956)	28° - 30°	(Strawn, 1961)
Optimum Activity	10° - 18°	(Job, 1955)	22° - 29°	(Johnson, 1960)
Final Preferred Temp. (Adult)	14° - 19°	(Fry, 1951)	27° - 28°	(Dendy, 1948)
Max. Tolerance (1 week)	25°	(Fry, et al, 1946)	35°	(Hart, 1952)
Max. Tolerance (1 hour)	28°	(Fry, et al, 1946)	38°	(Hart, 1952)

IV THE EFFECTS OF CHANGING WATER TEMPERATURE ON THE DEVELOPING EGGS AND EMBRYOS

A Under extreme weather conditions, temperatures of the water may rise quite rapidly for as much as 13° or 14° F.

1 Tester records the death of embryos as the result of a 2-day temperature rise from 61° to 73.5° (16.1° to 23.1° C).

2 Drops in temperature will also cause loss of nests as the parents abandon them. Lydell reported a loss of eggs when the water temperature dropped from 65° to 45° F (18.4° to 7.2° C).

3 Meehan observed that the smallmouth bass abandoned their nests when water temperature dropped from 58° to 48° F (14.4° to 8.9° C).

4 Kramer and Smith reported the death of largemouth bass embryos when temperatures dropped from the high 60's to below 50° F.

V LETHAL TEMPERATURES

A Brett lists upper and lower lethal temperatures for largemouth bass that previously have been acclimated to temperatures of 20°, 25°, and 30° C.

These are shown in Table 2.

Table 2. LETHAL TEMPERATURES OF LARGEMOUTH BASS

	High Temperatures	
Acc. Temp.		Lethal Temp.
20° C (68° F)	---	32.5° C (90.5° F)
25° C (77° F)	---	34.5° C (94.1° F)
30° C (86° F)	---	36.4° C (97.5° F)
	Low Temperatures	
Acc. Temp.		Lethal Temp.
20° C (68° F)	---	5.5° C (41.9° F)
30° C (86° F)	---	11.8° C (53.2° F)

B Similar tests made on bluegills indicated that they were more sensitive to high temperatures than largemouths but somewhat superior in their ability to withstand low temperatures. Similar information for spotted and smallmouth bass is apparently not available.

VI PREFERRED TEMPERATURES

A According to Fry, fish prefer a certain temperature range which is "the region, in an infinite range of temperature, at which a given population will congregate with more or less precision--a temperature around which all individuals will ultimately congregate, regardless of their thermal experience before being placed in the gradient."

B Ferguson lists field observations of the preferred temperature for largemouth bass as 26.6° to 27.7° C (79.9° to 81.9° F), spotted bass as 23.5° to 24.4° C (74.3° to 75.9° F), and smallmouth bass as 20.3° to 21.3° C (68.5° to 70.3° F).

C The preferred temperatures for largemouth and spotted bass were based, however, on field observations in Tennessee and the smallmouth from northern Wisconsin.

1 One might assume that smallmouths from northern Wisconsin would demonstrate a lower preferred temperature than this species in waters farther wouth where summer water temperatures normally greatly exceeded 21° C (69.8° F).

2 Laboratory tests with smallmouths showed the preferred temperature was 28° C (82.4° F), but such tests with both largemouths and smallmouths showed higher preferred temperatures than those recorded in field observations.

VII SUMMARY

The information presented does not define the environment but rather shows that the requirements of these fish are not very specific. It also shows that the early stages in the life cycle of these fish are more vulnerable to thermal variation.

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POTENTIAL EFFECTS OF THERMAL POLLUTION TO PACIFIC SALMON

I INTRODUCTION

A Investigators have usually regarded temperature as a variable to be tolerated, and if it couldn't be tolerated, then they attempted to determine its effects, mainly in regard to its effects on their experiments.

B As a result, the literature does not fully contain the data that are needed immediately to determine the allowable levels of heat that will not harm Pacific salmon.

C Because temperature affects physical, chemical and biological aspects, it is entirely possible to seriously and adversely affect salmon without directly killing them from heat death.

D In view of the above it is necessary to postulate some of the potential effects of thermal pollution, if only to cause the reader to realize that the ramifications of heat discharge can be very subtle but very potent.

II CLASSIFICATION OF THERMAL TOLERANCE

A All forms of aquatic life can be classified according to their tolerances of different temperature regimes.

1 Homoiothermic animals are the so-called warm-blooded thermal regulators, and in this case these are the higher vertebrates such as birds and mammals. These will probably not be affected by thermal pollution except as it influences their food supply.

2 Poikilothermic animals, on the other hand, are the so-called cold-blooded or thermal conformers. These animals maintain a body temperature very similar to the temperature of the water and they have no choice but to conform to the ambient water temperatures.

B We can further classify poikilothermic animals as to the range of temperatures which they will tolerate.

1 For example, stenothermal animals tolerate a narrow temperature range. They are both cold-water stenothermic animals such as salmon, trout, grayling, etc., which tolerate only a narrow range of temperature at the colder end of the spectrum, and there are warm-water stenotherms which tolerate only a fairly narrow range of temperatures at the upper or warmer end of the spectrum; these are the tropical fish, guppies, etc.

2 In fresh water we have both cold-water stenotherms and warm-water stenotherms, as well as a third class, the eurythermals that tolerate a wide range of temperatures and span the spectrum from about 32° F (0° C) to as high as 99° F (37° C). These are the bass, bluegill, carp, etc., with which we are so familiar and describe generally as rough or pan fish.

3 Most saltwater poikilotherms are stenothermal and tolerate a narrow temperature range either at the upper, at the middle, or at the lower range.

B We can further subdivide temperature tolerance by examining a single species, and we usually find that some life stages of that species will be more demanding, more sensitive, more stenothermal than other life stages.

1 For example, embryonic stages are usually more stenothermal than any other life stage.

2 This is because cell division processes are occurring which produce the primitive cells that eventually produce whole organs.

3 Any interference with these cell division processes can have serious repercussions and may latently cause the death of the organism.

C It should also be noted that some tissues are more stenothermal than other tissues and that the temperature tolerance of the organism varies accordingly.

1 For example, brain tissue is very easily injured by high temperatures that do not adversely affect many other organs.

2 Another heat-sensitive tissue is that of the gonads and high temperatures can adversely affect spermatogenesis.

III GENERAL EFFECTS OF TEMPERATURE

A The general effect of a temperature increase is that a given biological reaction will be accelerated by about 100% per 10° C rise in temperature.

B Another general effect of a temperature is noted in the time required for fish eggs to hatch.

1 For trout, the general rule is that they will hatch in 50 days when they are held at 50° F.

2 Higher temperatures will cause the eggs to hatch in less than 50 days, whereas colder temperatures will cause the eggs to hatch in more than 50 days.

3 One should not imply that the additional heat and the shortening of the hatching time are beneficial to the resulting fry.

4 Temperatures above approximately 62° F usually have produced extensive mortality among trout and salmon eggs.

5 Furthermore, those eggs that are incubated at higher temperatures, and subsequently hatch sooner, usually produce fry that are smaller and less robust than those which are incubated at colder temperatures for longer periods of time.

IV OXYGEN CONSUMPTION, ETC.

A Oxygen consumption is a function of temperature, up to a certain point at least.

1 Given an organism that is metabolizing at a standard rate, a 10° C rise in temperature will increase the oxygen consumption by approximately 100%, and this will remain a fairly linear response until the organism becomes somewhat stressed.

2 After the stressful level of heat is reached, the relationship between oxygen consumption and temperature becomes nonlinear and a 10° C rise in temperature may cause the organism to consume oxygen at a rate of over 200% above the previous level.

B The effects of temperature on cardiac and ventilation rates have been discussed somewhat earlier, but suffice it at this point to say that high temperatures can cause extremely nonlinear ventilation rates.

1 Quite probably this effect is mediated by chemical receptors which test the oxygen and carbon dioxide levels of the blood and in turn call for more water over the gills, more ventilation, to try and balance the resulting inequities.

2 But whatever the mediating factors may be, the net effect is to have water pumped over the gills faster than the heart is beating, thus wasting effort to some extent.

V ENZYME SYSTEMS

A The effects of temperature on enzyme activity is extremely important because the enzymes provide almost all the biochemical machinery by which all the body functions are performed.

1 *In vitro* studies amply demonstrate that enzyme activity closely follows Van't Hoff's law and is generally increased 100% by a 10° C rise.

2 These circumstances do not adequately describe the situation *in vivo* where feedback and other protective mechanism alter these circumstances.

B Another problem that may result from excessive enzyme activity is that the substrate may produce an excessive level of a toxic product such as ammonia.

1 If the production of a toxic product occurs at a rate faster than the cell can handle this material, the result may affect the other cellular processes which are dependent upon that particular metabolic pathway, and it can even cause the death of the cell itself.

VI TOXICITY

A A discussion of the effects of toxicity and temperature would be incomplete without pointing out that toxicants cause their action by attacking one or more enzyme systems.

1 Higher temperatures can increase toxicity because higher temperatures cause greater metabolic demands, hence they allow less interference with any of the metabolic processes.

B While it is true that higher temperatures generally increase the effects of toxicants, there are notable exceptions to this generalization.

1 For example, DDT is less toxic at higher temperatures than it is at lower temperatures.

2 The extent to which other insecticides or other toxicants display a similar effect is generally unknown.

VII NUTRITION

A The effects of higher temperatures on nutrition are poorly understood but we can generalize to say that higher temperatures cause higher rates of metabolism, hence higher rates of cell destruction, hence higher maintenance cost to the organism.

1 As discussed earlier, the production of gametes is a process which can be very adversely affected by either excessively high or excessively cold temperatures.

2 Photo-period seems to trigger the initial reproductive development and gameteogenesis processes.

B Studies of the effects of high temperatures on gamete maturation, that is, ripening of the sex products, have been attempted on Pacific salmon, but these studies have always been frustrated by serious outbreaks of disease.

1 Where disease was not an overwhelming problem, the females and males delayed their sexual maturation considerably when held at high temperatures.

2 As a result, the associated hatcheries were not able to collect spawn in early September, and in some cases this was delayed to as long as December.

C The effects of altered spawning time could be quite profound.

1 Late spawning may be rapidly followed by winter temperatures which can drop so low that they actually kill the embryo.

2 But a more subtle effect would be that the young fish would probably hatch late and may not have the growth needed to allow them to migrate successfully.

3 Additional effects of high temperatures to embryonic development include teratogenesis, or monster formation, causing somatic aberrations which may produce Siamese twins or two heads on one body or two tails on one body and these teratogenic embryos do not survive.

X GROWTH

A Growth and maturation can also be influenced adversely by elevated temperatures. Mention has already been made of the effects of elevated temperatures on nutritional requirements.

1 It is widely recognized that coho salmon smolts that grow too fast and are too large at the time of migration usually return precociously (called Jacks) within seven or eight months after they were liberated.

2 This is one year too soon and the result is that these weigh about one-third less than normal adult fish and these Jacks are generally incapable of reproduction.

XI NITROGEN EMBOLISM

A Nitrogen embolism or "gas-bubble disease" is another problem associated with temperature increments.

1 Heat added to water will decrease the solubility of dissolved gases and this may cause gas bubbles to form internally in the fish.

2 This may produce a blockage of capillary beds, or in more extreme cases cause undue pressure on nerves or form gas locks in the coronary chambers.

3 A more subtle effect of supersaturated water is that it may form a gas bubble in the mouth or buccal cavity of fry.

a This blocks the passage of water across the gills and in essence suffocates the fish.

b After death, the bubble is lost and there is no evidence of what killed the fry.

c Similarly, recent studies have shown that adult salmon killed by nitrogen embolism lose all of the characteristic symptoms (gas blisters under the skin, etc.) thusly destroying within 24 hours the evidence that indicated the cause of death.

B When adult salmon were acclimated to sublethal levels of supersaturated nitrogen, these fish could tolerate essentially no temperature increase or vigorous exercise. This is particularly important in view of the fact that the Columbia River is supersaturated from its mouth to Grand Coulee Dam throughout the summer runoff when water passes over the spillways.

XII TISSUE REPAIR

A One must consider the potential effects of thermal pollution to tissue repair processes in Pacific salmon. When migrating upstream to spawn, these fish are continuously being abraded and cut by their vigorous attempts to ascend falls, rapids and fishways.

B Hatchery managers have noted that injured salmon will repair these cuts and abrasions provided they are held in "cold water." Fish held under similar conditions, but in "warm water," did not repair their wounds, and unfortunately, developed sufficient fungal and other infections to produce a high incidence of mortality. The exact tolerable levels for tissue repair are as yet undefined.

XIII SUMMARY

The reader should be aware that even slight increases in temperature may have a profound effect on Pacific salmon. The precise levels which will not adversely affect such vital aspects as enzyme activity, reproduction, downstream migration, nutritional requirements and tissue repair have not been determined. One can only suggest that all due caution should be exerted in establishing permissible water temperature standards, until the potential physiological effects are better understood and clarified.

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This outline was prepared by John F. Wooley, Biologist, Manpower & Training Branch, Pacific Northwest Water Laboratory, FWQA.

EFFECTS OF TEMPERATURE ON PACIFIC SALMON

I INTRODUCTION

A Pacific salmon (Oncorhynchus spp.) are unique in several ways:

1 They provide the most important commercial fin-fishery in the United States, in addition to an invaluable sport fishery.

2 They migrate between the ocean and their natal stream where they spawn only once before death.

3 They are cold water stenothermal fishes, and hence thermal pollution presents a greater threat to salmon than possibly any other fishes.

4 For these reasons, and because projected power requirements will necessitate steam-electric stations, thermal pollution presents a particularly urgent problem in the Pacific Northwest.

II EFFECTS ON LIFE STAGES

A Temperature effects on each life stage (egg, fry, fingerling, yearling and adult) were considered individually for the five species of Northwestern Pacific salmon (sockeye, chinook, coho, pink and chum).

B Particular emphasis was given to the following subject categories:

1 Lethal and Optimum temperatures and the effects (lethal and sublethal) of temperature on reproduction and development.

2 Movement and activity (including migration).

3 Feeding and growth.

4 Compound stress (changes in conjunction with limiting conditions such as oxygen).

5 Acclimation

6 Disease

7 Physiological responses more or less at the cellular level

C Whenever ambient temperature was reported, its equivalent in degrees Celsius or Fahrenheit was added in parenthesis.

III THERMAL TOLERANCE

A The principles involved in the thermal requirements of fishes were described by Brett (1956).

1 The fundamental requirement is an external temperature that is best suited for internal tissues.

2 Other important principles emphasizing the multiple role of temperature are that warm water fishes generally have a higher level of thermal tolerance than those which inhabit cold water.

3 Lethal levels are very important in setting geographical distribution.

4 Performance is best in the region of preferred temperature.

5 Sensitivity to small temperature gradients may also act as a directive factor.

B Temperature can be a lethal, a loading, or an inhibiting stress to salmon (Brett, 1958).

1 Beyond the thermal tolerance zone is a high stress area that causes rapid death to salmon exposed to such extremes.

2 Within the thermal tolerance zone, loading stress encloses an area where growth and swimming would be impaired seriously.

3 At still lower temperatures an inhibiting stress level may affect the normal endocrine balance necessary for spawning.

C Salmonidae have the least tolerance to high temperatures and their maximum upper lethal temperatures barely exceed 25° C (77° F) (Brett, 1956).

1 The ultimate lethal levels between salmon and goldfish can differ by as much as 17° C (30.6° F) (Brett, 1960).

2 Most salmonid eggs suffer when the water temperature goes above 55° F (12.8° C) or below 35° F (1.7° C), but the tolerance level of later stages in most species falls to 32° F (0.0° C) (Royce, 1959).

D Salmonid fish have a temperature tolerance zone that falls between 38 and 65° F (3.3 and 18.3° C).

E Lethal zones for some species exist from about 55 to 77° F (12.8 to 25.0° C) and from 35 to 32° F (1.7 to 0.0° C) (Brett, 1960).

F Davis (1961) stressed that salmonids require water between 45 and 55° F (7.7 to 12.8° C). The preferable temperatures are 48 to 52° F (8.9 to 11.1° C).

IV ACCLIMATION

A Temperature changes require continuous acclimation while governing the scope for the metabolic rate (Brett, 1956).

1 Temperature tolerance also depends on acclimation (Brett, 1967).

2 There is no single end point so high and low temperatures can be lethal to young salmon over a range of about 21.5 to 25° C (70.7 to 77° F) and 7 to -0.1° C (44.6 to 31.8° F), depending on the species and acclimation.

B Temperature, if acting alone, can determine the distribution of fish in laboratory apparatus (Ferguson, 1958).

1 Factors which interfered with temperature responses included light, feeding routines and social behavior.

2 The level of thermal acclimation influenced the range of preferred temperatures.

3 The preferred temperature was higher than the acclimation temperature at low thermal acclimations, but this difference decreased to a final preferendum where both coincided.

V EARLY DEVELOPMENT

A The rate of development and time of emergence of young salmon is strongly dependent upon the temperature during development (Hoar, 1958).

1 At higher temperatures the growth rate is accelerated, but the size of the fish produced is reduced, primarily due to higher maintenance requirements.

2 Larger emergent fry have a better chance of survival.

3 Emergence time, which is affected by temperature, is important because through acceleration or deceleration of emergence, fish could be placed in an unfavorable environment either from the standpoint of predator activity or available food.

VI MIGRATORY RELATIONSHIPS

A Optimum water temperatures for salmonid migration in the Northwest was suggested to range from 45 to 60° F (7.7 to 15.6° C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967).

B Burrows (1963) also cited these temperatures as best for the upstream migration of salmon.

C The peak of the seaward migration of juvenile salmon was reported to occur regularly at temperatures of 10° C (50° F) or lower (Keenleyside and Hoar, 1954).

D Temperature was not believed to play a primary role in the timing of migrations (Hoar, 1958).

1 Juvenile salmon migration is caused primarily by increased thyroid activity according to a hypothesis by Baggerman (1959).

2 External factors, including increased photoperiod and temperature, act along with other intrinsic factors to induce a preference for seawater and a disposition to migrate.

3 It was emphasized that migration is probably not induced by any one factor, but is a result of interaction between a number of factors.

E Water temperature also controls the activity of fish predators; hence it influences degree of predation encountered by salmon fingerlings (Burrows, 1963).

1 The preferred or optimum temperatures of both the migrant and the predator influence migrant survival.

2 Warmer temperatures generally favor predation.

XII OXYGEN RELATIONSHIPS

A The decreased solubility of oxygen at increased temperatures was discussed by Shaw (1946).

1 His studies stressed the markedly increased oxygen consumption by salmon and trout at higher temperatures.

2 Normal consumption increased 400 percent from 45 to 68° F (7.7 to 20° C).

B Leitritz (1962) emphasized that a rise in temperature, as well as activity and feeding, will increase the oxygen requirements in salmon.

XIII DISEASES

A Most fish diseases are favored by increased water temperatures (Davis, 1961).

1 While higher water temperatures drastically increase the effects of kidney diseases, furunculosis, vibrio disease and columnaris disease in young salmon (Ordal and Pacha, 1963), constant water temperatures are also conducive to disease development (Burrows, 1963).

B The causative agent for columnaris disease, Chondrococcus columnaris, ordinarily attacks fish at comparatively high temperatures (Davis, 1961).

1 The optimum temperatures for growth of C. columnaris have been given as 25 to 31° C (77 to 87.8° F), and although it will grow at much lower temperatures, it is rarely injurious at temperatures below 15° C (59° F) (Garnjobst, 1945).

2 Borg (1948) stated that the disease progressed rapidly and produced recognizable lesions when the temperature was above 18° C (64° F).

C An average water temperature below 50° F (10° C) was believed by Fish (1944) to represent the optimum for tissue repair and also to adversely affect the growth of columnaris disease.

1 He showed that the mortality to prespawning injured salmon could be kept to a minimum by retaining the fish in an average water temperature not exceeding 50° F (10° C).

2 Davis (1961) believed that infections were most likely to occur at water temperatures above 70° F (21.1° C) among fish that have been handled or otherwise injured.

D The major damage by columnaris disease to Columbia River salmon was believed by Ordal and Pacha (1963) to occur to juvenile, rather than adult fishes.

1 These authors suggested that high-virulence strains of C. columnaris in the Columbia River Basin might be due to increased multiplication, hence increased likelihood of mutation, as a result of higher water temperatures.

2 Field observations have confirmed that conditions at fish ladders can be important factors in the incidence of columnaris disease (Fjuihara and Olson, 1962).

E Furunculosis disease affects chiefly the salmonid fishes (Davis, 1961).

1 These pathogenic bacteria grow best at comparatively low temperatures with an optimum at 10 to 15° C (50 to 59° F).

2 The disease is likely to reoccur at a hatchery if the temperature of the water is raised above the optimum.

F Borg (1948) isolated Cytophaga psychrophila, the causative agent for "cold-water disease."

1 This disease is found at low water temperatures and disappears at 55° F (12.8° C).

G Fungal infection by Saprolegnia sp. causes mortality chiefly by secondary infection in previously injured or debilitated fish.

Mortality was delayed when olding ponds were kept at temperatures below 58 to 65° F (14.4 to 18.3° C) (Fish, 1944).

H Ceratomyxa sp. was reported to be most virulent to Columbia River salmon when water temperatures approached 65° F (18.3° C) (Snyder, 1968).

I "Gas-bubble disease" occurs in the Columbia River when the water becomes supersaturated with nitrogen.

1 During the spring and summer runoff period, large amounts of water plunge over the spillways, entrapping and dissolving excessive amounts of air.

2 This water can initiate the formation of gas bubbles in the blood and tissues of salmonids resulting in death (Davis and Snyder, 1967); Snyder, 1968a).

3 Thermal additions would increase the seriousness of the existing problem.

IV SUMMARY

An excellent analysis and review of thermal plant and thermal pollution problems and their relationships with salmonid fish in the Columbia River and the Pacific Northwest was provided by Snyder (1968a). Delayed migrations, nitrogen gas effects, and effects on predators, competitors and diseases were among the problems that were emphasized. The problem of how temperature increases can be compounded by low flows and tidal fluctuations was discussed by Snyder (1968b). Tidal action causes flow reversal in the lower Columbia where thermal power plants are planned.

This could force juvenile migrants to move prematurely from the estuary into cooler ocean water. Juvenile salmon also could be subjected to a 20° F (11.1° C) thermal shock if they are passed through thermal electric plant cooling condensers. While the fish may not be killed directly by a 20° F (11.1° C) increase at low river temperatures, this increase could be fatal when the river temperatures are approaching 70° F (21.1° C).

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RESEARCH ON THERMAL EFFECTS: FISH

I INTRODUCTION

The most obvious effects on the biota and the effects of most concern to the public will be the effects of temperature on fish production. Since fish are so important for both commercial and recreational use, these are the organisms currently receiving the most attention in thermal effects research.

Two main areas of concern are: 1) the limiting temperatures for fishes of special interest; 2) chronic effects of heat addition to fish of special interest.

II LIMITING TEMPERATURE RESEARCH PROGRAMS

A Priority questions at FWQA's Water Quality Laboratory at Duluth, the National Marine Water Quality Laboratory in Rhode Island and with the Bureau of Commercial Fisheries research barge in the Columbia River in Oregon are those pertaining to limiting temperatures for fish.

B The Duluth Laboratory is working on limiting temperatures and egg development.

1 Some studies have been completed on optimum temperatures for northern pike growth. The optimum temperature for growth was 21° C.

2 Duluth has not started a study using brook trout which will be held at temperatures ranging from 10 to 21° C to see the effect of temperature on spawning.

3 Wild trout eggs will be tested at different temperatures. These eggs and fry from these eggs will be subjected to thermal shock to see what effect it has on them and to see if some eggs and fry will become acclimated if raised at higher temperatures from the start.

C The Duluth studies are being planned so we can hopefully be able to apply the ideas more widely than some of the research has allowed in the past.

1 Work has been started on tolerances of pike, white sucker and lake herring.

2 These fish are representative of the general types found in nature.

a Lake herring naturally live in deep, cold water with a stable temperature range.

b Pike live in a habitat that has a greater temperature range than the herring but less of a range than the suckers.

c With these three organisms all ranges are included.

D Tolerance data from these forms will be used in a broad sense so it may be applied to fish of a similar ecological type.

Presently we do not have time to wait until tolerances can be determined for every species.

E Researchers in Rhode Island are working with marine fishes.

F The studies on the Columbia River are mainly concerned with the salmonid fishes.

III RESEARCH ON CHRONIC EFFECTS OF HEAT ADDITION

A Lethal temperatures of fish are being determined first, but long range studies covering all life stages are needed.

B Temperature preference and avoidance studies are being conducted by Battelle Northwest on salmon in the Columbia River.

C Sandy Hook Marine Laboratory is looking at the same problem using other types of fishes.

D Oregon State University is doing research on the relationship of temperature to metabolism in fish.

E Work is being done by the Pacific Northwest Water Laboratory, Corvallis, Oregon, on the effects of temperature on enzyme activity and at the Columbia River on effects of temperature on egg and fry survival.

F The Fisheries Research Board of Canada at Nanaimo, B.C., have been studying the relationship of acclimation to lethal temperatures.

IV SUMMARY

So far, almost all fish research has been directed at the individual or single species level. This basic data is needed first but we must go on to an ecosystem approach to really assess the complete effect of temperature.

ACKNOWLEDGMENT:

Material for this outline was taken from the Technical Seminar Paper on Biological Effects by Ronald Garton, PhD.

This outline was prepared by John F. Wooley, Biologist, Manpower & Training Branch, Pacific Northwest Water Laboratory, FWQA.

BENEFICIAL EFFECTS OF HEAT ADDITIONS

I INTRODUCTION

Though the predominant results of heating our natural waters are detrimental to the propagation of game fish and reduce the assimilative capacity of a stream, there are some beneficial effects due to the warmed waters. The total amount of waste heat produced per year, however, is so great that even if all the suggestions for use of waste heat for beneficial use were adopted, the excess heat remaining would still be a problem. For example, the waste heat from power generation would be more than sufficient to heat every home in America.

II DISTRICT HEATING

A Possibly the most advanced use of waste heat is for district heating (Santala, 1966).

B This has been used in Finland for the 20,000 inhabitants of the city of Tapiola Garden since 1953.

C The English also have used waste heat for district heating.

III INCREASED BIOLOGICAL PRODUCTION

A Though it has been observed on the Potomac River and many other rivers that fishermen tend to congregate in the winter in the heated pools below power stations for better fishing, it has also been noted that fishing is poorer in the summer (Elser, 1965).

B Research into the possible increased growth of fish below steam electric generating plants has been underway at least since 1953. However, definitive statements are still not possible.

  1 In 1953, the Central Electricity Generating Board determined the rate of growth of flounder at the Newton Abbot Generating Station (Iles, 1963a).

  2 Some of the earlier work had dealt with the possibility of utilizing increased yields of algae for food material and talked of farms below the sea (Raymont, 1957).

  3 In 1962, the experiments were extended to feed the algae to clams to help solve the problems of harvesting the algae and to ease the preparation of the final product (Ansell, 1962). The economics of the production has not been completed.

C Mihursky has suggested a variety of possible constructive uses of thermal additions to estuaries, including a complete recycling of organic wastes from humans to sewage treatment plants to inorganic fertilizers to algae, zooplankton, shellfish and fish to food processing to people to organic wastes, etc.

  1 Utilization of the waste heat could be made at the sewage treatment plant, in the enhanced growth of algae, zooplankton, shellfish and fish, and district heating (Mihursky, 1967).

  2 Studies of individual sections of this cycle are being carried out.

D At Turkey Point, shrimp farming in the effluent of the Turkey Point Power Plant is being studied. Pompano cultivation will also be studied there.

E Lobsters may also benefit from heated waters.

  1 It has been suggested that the lower yields of lobster in recent years may be due to cooler waters in their breeding grounds off the Marine Coast.

  2 It has been further suggested that the heated discharge from cooling stations could be used to warm shoreline coves to increase lobster yields.

F Long Island Lighting Company at Northport, New York is experimenting with the aquaculture of oysters in the heated discharge from their nuclear power plant (Kovaly, 1968).

G A report from the Electric Boat Division has suggested that it might be possible to raise 18 million kilograms (8.63 million pounds) of warm water fishes annually by using thermal discharges.

1 Present annual per capita consumption of fish is approximately 10.5 pounds (Lerner, 1968).

2 Perhaps the most original suggestion is that heated waters in England be used to raise ornamental fish, some of which sell for over $140 per pound (Isles, 1963a).

H Some inadvertant beneficial use of the warmed waters may have already occurred. The growth and spread of the American hard-shell clam in English waters may well have been due to the warming effect of cooling water effluents (Ansell, 1963).

IV CONTROL OF MARINE FOULING

A The reversal of the flow of cooling sea water streams through the intake pipes in order to raise the temperature to limit the creatures inhabiting the pipes is not new.

1 The use of heated waters for the control of mussels for a station on the coast of California is shown to be less expensive than the use of chlorine (Chadwick, Clark, Fox, 1950).

2 A followup of the original work 10 years later shows that thermal control was still the most successful as well as the most practical means of control of fouling (Fox and Corcoran, 1958).

V WATER WORKS TREATMENT

A Many studies have been made on the effect of temperature on water treatment processes (Burnson, 1938; Camp, Root, Bhoota, 1940; Renn, 1957; Velz, 1934).

1 Renn sums up the experience to that time (1956) by noting that Fair and Geyer (1954) find that "the efficiency and effectiveness of flocculation and of filtration of floc-bearing water rises with rising temperatures."

2 Most other authors agree though Velz (1934) disagreed.

B Camp's studies (Camp, Root, Bhoota, 1940) showed that the optimum condition for flocculation is determined by three variables--iron-alum dose, pH, and temperature.

1 Velz's findings may be in agreement with this since he also showed that isoelectric point of the flocculating system shifts drastically with temperature.

2 Because of this increased efficiency in flocculation, the State of Pennsylvania's Committee on the Effects of Heated Discharges found in 1962 that savings in chemicals for water treatment would be 30 to 50 cents per million gallons for each 10° F rise in temperature (Arnold, 1962).

3 This may be compared with an average cost of chemicals of $14 for treating water and a range of $3 to $30 per million gallons.

VI WASTE TREATMENT

A There is a considerable body of literature on the effects of heating sludge, but little information on the effects of temperature greater than 60° C.

1 Recently, raw sewage has been heated to 100° C to determine if there were any improvements in settling efficiency.

2 Crotty, et al (Crotty, Feng, Skrinde, Kuzminsky, 1968) found that heat treated wastes were more homogenous and settled faster. However, further work is required.

3 Earlier German work cited by Crotty on preheating sewage and raw sludge to 100-120° C shows that they will be more amenable to sedimentation and biological treatments.

VII IRRIGATION

A The intake of the Oroville Power Plant on the Feather River was especially constructed at considerable extra expense to draw water from various levels to avoid damage to downstream agricultural interests by excessively cool water (Raney, 1963).

B The same results could have been achieved by mixing the heated waters from a thermal power station with the discharge from the hypolimnion of a storage reservoir.

VIII ICE-FREE SHIPPING LANES

A A recent study by Dingman, et al (1968) has shown that it should be possible to keep significant portions of the Saint Lawrence Seaway open the year around by the judicious location of central station electric power complexes.

B This would save transportation costs of several million dollars per year.

C It is estimated that a 600 mw reactor could keep a stretch of the river between 11 and 16 miles ice-free.

D No study was made of the ecological effect of such an undertaking, however.

IX WATER AND SEDIMENT DISCHARGE

A Since the viscosity and density of water decreases with temperature, a change in temperature should have an effect on both sediment transport and water flow.

1 It had previously been thought that the variation of only a few degrees would have a small effect (Burke, 1966).

2 More recent data, however, suggests that these effects may be quite important (Burke, 1969).

B Colder water is more viscous than warmer water and therefore has a higher carrying capacity for sediment than does warmer water.

1 In warmer water, coarser material settles out and so for any crossing in the river (which acts as a submerged weir) there is less flow past that cross-section for the same stage.

2 Decreasing water temperature may be assumed to make a difference of 10 to 20 percent in expected discharge for a given state (Burke, 1969).

3 Sudden rises in temperature may cause such a deposition of coarse material to ground ships following sailing lines.

C Studies by Colby and Scott have indicated that changes in temperature affect bed material discharge in complex ways (Colby and Scott, 1965).

1 The thickness of the laminar sublayer is changed with the temperature, but it is usually only a small effect.

2 The vertical distribution of suspended material is greatly affected by temperature changes and indicates an approximate doubling of bed material discharge when temperatures drop from 80° F to 40° F, assuming that the mean velocities, depths, and sizes of bed sediments remain constant.

3 Finally, the bed configuration and therefore, the resistance to flow are effected by changes in temperature. The effect may be large or small.

D Colby in an earlier summary of fluvial sediments (Colby, 1963) had noted that the full velocities of sediment particles increase with an increase in water temperature.

1 For particles larger than 1 mm, however, the percentage increase is small.

2 For sediments in the size range 0.1 to 0.4 mm, fall velocity, vertical distribution and discharge of sediments is greatly affected by temperature changes (Colby, 1963).

E Franco (1968) in a more recent study confirms some of these results and finds that the effects of water temperature on bed load appear to be mostly in the formation of the bed and bed roughness.

X WATER SUPPLY SOURCE

A A serendipitous benefit was obtained in Henderson, Kentucky, when it was found necessary to replace the town's water supply system.

1 Over one quarter of a million dollars was saved by the use of the condenser cooling waters as the intake to the tower's water supply system (Highland, 1962).

2 Fortunately, no chemicals were added to the intake water and the warmer water had not to that date caused any problems.

XI SUMMARY

Though it has already been pointed out that it is highly unlikely to find beneficial uses for all the heat that would ordinarily be wasted to the atmosphere or hydrosphere, there are some uses, as already indicated, which could reduce the negative effects of present day discharges.

ACKNOWLEDGMENT:

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THERMAL POLLUTION FROM NATURAL CAUSES

I INTRODUCTION

Although the term "pollution" is almost universally reserved for use in describing the results of man's activities, at times it can also define adverse environmental effects from other causes. Adverse thermal effects from natural causes have been observed since the first man appeared on the earth. If one accepts the biblical story of Adam and Eve, he could easily imagine Adam, on a hot summer day, telling Eve how difficult it was to work in the extreme heat, or in wintertime, the two of them huddling together for added protection from the cold.

In this outline, consideration will be given to the natural thermal sources and how they may affect the aquatic environment.

II NATURAL HEAT SOURCES

A The energy budget - as related to a water mass, the energy or heat budget is frequently expressed as: (Randall, 1962):

$$Q_t = Q_s - Q_r - Q_b - Q_h - Q_e + Q_v$$

where Q_t = increase of energy stored

Q_s = solar radiation incident to water surface

Q_r = reflected solar radiation

Q_b = net energy lost through long-wave radiation

Q_h = conduction loss to atmosphere

Q_e = evaporation heat loss

Q_v = advective heat loss or gain

This is shown schematically by Figure 1.

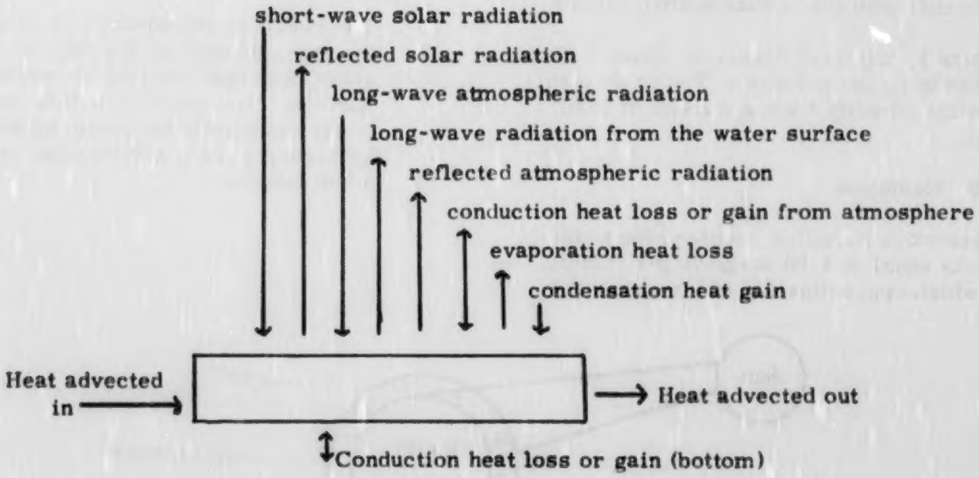
short-wave solar radiation
reflected solar radiation
long-wave atmospheric radiation
long-wave radiation from the water surface
reflected atmospheric radiation
conduction heat loss or gain from atmosphere
evaporation heat loss
condensation heat gain
Heat advected in
Heat advected out
Conduction heat loss or gain (bottom)

FIGURE 1

HEAT FLOW - RELATED TO WATER MASS

Although the energy budget equation is used as a base for predicting thermal pollution, at this time we will use the schematic (Figure 1) only as a means of identifying heat sources which may affect the environment.

B Volcanic Heat

Volcanic heat or heat from the earth's core may contribute considerable thermal energy to the aquatic environment. This heat is, however, usually confined to areas of hot springs and volcanos.

Some of these areas have become famous as resort areas and as such the volcanic heat in the environment is not considered pollution even though this heat may cause considerable deviation from the norm.

Studies of the aquatic biota in Yellowstone National Park have revealed some very definite variations from the normal. It is highly likely these forms have adapted to their "hot water" environment over a period of many thousands of years.

Although some proposals have been made to tap heat from these sources, until this time man has not made any significant alteration in the release of volcanic heat from the earth's core into the habitable environment.

In Figure 1, this heat source is shown as heat advected in by the hot water flow or by heat conduction directly from a stream or lake bottom.

C Solar Radiation

Short-wave radiation received from the sun is equal to 1.95 langleys per minute, of which approximately 40% reaches the earth's surface on an average of about 8000 calories per square meter per minute. The balance of radiation received from the sun is either reflected or absorbed by the atmosphere. Approximately 45% of the total received (0.88 langleys) is reflected back into space by the atmosphere. The atmosphere absorbs about 15% of the total (0.29 langleys). This latter helps to maintain atmospheric temperature and promote its circulation.

Although a total of 19,500 calories per square meter per minute reaches the earth with the sun directly overhead, the amount of this short-wave radiation which reaches the surface to be absorbed by a water mass is affected by:

1 The duration of sunlight per day, which is a factor of season and latitude.

2 The elevation of the sun. When the sun is directly overhead, its rays have the least distance to travel through the gas molecules making up the atmosphere. As the sun moves from the vertical this path increases (Figure 2) permitting greater absorption and scattering of the solar radiation by gas molecules in the air.

The result of phenomenon is to alter the rate, throughout the day, at which solar radiation reaches the earth's surface. The function of this change is approximately parabolic as shown by Figure 3 for a selected day at 45 north latitude.

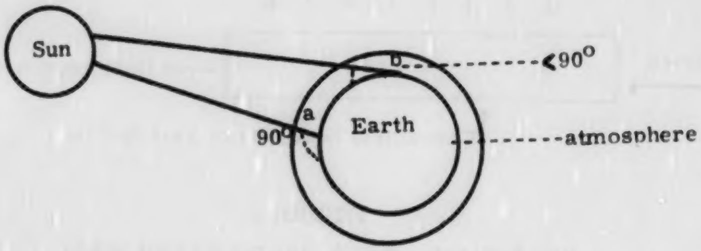

FIGURE 2

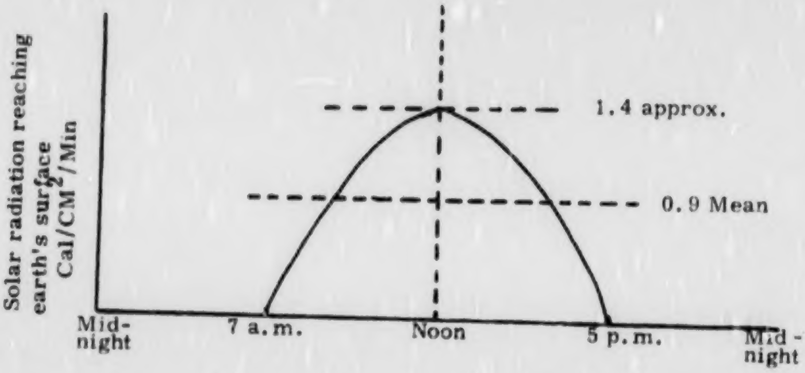

FIGURE 3

3 Cloud cover affects amount of energy reaching the surface because of absorption and scattering of the radiation in and by the water molecules.

4 In addition to direct sunlight the surface of a water mass also receives skylight radiation from sunlight that has been scattered by the atmosphere. This factor becomes more important in higher latitudes where the angle of the sun from the vertical decreases the amount of direct solar radiation and increases atmospheric scattering.

5 The reflective condition of the water surface, for example, calm, smooth surface or windswept waves is another important factor because as much as 2 to 50% of solar radiation reaching the water surface will be reflected from the surface depending upon surface conditions.

D Long-wave Radiation

Short-wave solar radiation absorbed into the atmosphere is altered to long-wave radiation in which form it may reach the water surface to be absorbed. Likewise long-wave radiation is lost from the water mass into the overlying air. Whether or not the long-wave radiation results in a net gain or loss of heat in the water mass is dependent upon temperature of the atmosphere, the water, and humidity.

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THERMAL POLLUTION RESULTING FROM MAN'S PHYSICAL ALTERATIONS OF THE ENVIRONMENT

I INTRODUCTION

Heat as a pollutant has been shown to have numerous adverse effects on water and the aquatic environment. Because of these effects, we should examine activities of man that may tend to change the environment in such manner as to affect the natural thermal regime of our waterways.

II RESERVOIR CONSTRUCTION

Reservoir construction has long been considered as an environmental change which affects the aquatic environment. This affect may take one of two routes to alter the downstream thermal regime.

A Bottom withdrawal of cold water causing a somewhat lower stream temperature than normally experienced during the summer months. The solar energy absorbed by the water mass is retained within the reservoir in the upper layer or epilimnion. Often this heat energy promotes algal blooms. During the die-off period, the dead algal cells settle to the thermocline and decompose. In some instances, this decomposition produces hydrogen sulfide which, if discharged to a stream, will result in a fish kill.

B Surface discharge from reservoir releases the epilimnion waters which, during transit through the reservoir, have stored solar energy in the form of heat. The discharge thus elevates downstream water temperatures.

Whether or not either of these conditions will adversely affect the downstream ecology can only be determined on a case by case basis and evaluation of the environment and water use.

Heat storage is frequently shown by the equation:

$S = I - O + R \pm C - E$ Where:

S = heat storage in reservoir

I = heat in inflow waters

O = heat in outflow

R = net energy absorbed from radiation

C = sensible heat exchange

E = evaporation heat loss

Most of the heat entering the reservoir does so as either advected heat in the inflow or from radiation with radiation usually being the greater. This can be readily seen by analyzing the difference in surface area (stream surface/reservoir surface) open to the sun as a result of the impoundment. Inasmuch as a mean rate of approximately 8000 to 9000 calories per square meter per minute reaches the water surface during daylight hours, considerable energy can be added to the water mass because of the increased water surface exposed. If alternate sites are available, the impoundment area should, if possible, be oriented to minimize absorption of solar radiation.

III LOGGING PRACTICES

Logging in such manner as to completely expose a stream to solar radiation can add considerable heat to the flowing water. This can best be shown by an example problem.

Assume an area to be logged will remove the shade and completely expose a stream for a distance of 1000 feet. This small stream has an average velocity of 0.5 feet per second.

Incoming radiation is 1.4 langleys per minute and the albedo is 0.02. Find the energy added to the stream as a result of shade removal. Neglect change in long-wave radiation, sensible heat exchange, and evaporation. Then:

$S = R - (R_s - R_f)\,t$ where:

S = additional heat stored in the water mass

R = net energy absorbed from radiation

R_s = short-wave solar radiation

R_f = the reflected solar radiation

t = time of exposure to sun's rays

$R_f = aR_s$

a = albedo (reflectivity of the water surface)

$$S = 1.4 \frac{\text{Cal}}{\text{CM}^2\ \text{Min}} - (1.4 \frac{\text{Cal}}{\text{CU}^2\ \text{Min}})(0.02)$$

$$\left(\frac{1000 \text{ ft sec}}{0.5 \text{ ft}}\right) \left(\frac{\text{Min}}{60 \text{ sec}}\right)$$

$$S = (1.37 \frac{\text{Cal}}{\text{CM}^2\ \text{Min}})\ (33.3 \text{ min})$$

$$S = 45.7 \text{ calories}/\text{CM}^2$$

Thus, in this short stretch each centimeter of stream width will absorb more than 45 calories. If the stream is shallow, say an average depth of about 4 inches, the water temperature would rise on the order of 4.5°C or 8.1° F.

Although the problem was simplified somewhat by ignoring sensible heat exchange, long-wave radiation and evaporation, an error of sufficient significance was not introduced to invalidate our result. It becomes apparent that serious consideration should be given to protecting water quality by leaving vegetation along stream banks to shade the water surface from the sun's rays.

IV IRRIGATION RETURN FLOW

It has been pointed out the effect to be expected when water is diverted for irrigation. In instances of ridge and furrow irrigation, water is exposed not only to the heating caused by direct solar radiation, but also by sensible heat exchange from the soil of solar energy absorbed by the earth prior to application of irrigation water. In this case, however, evaporation becomes a very significant factor in helping to reduce the amount of heat stored in irrigation return flow waters. In the western United States where irrigation is widely practiced, elevated stream temperatures have been frequently observed.

V SUMMARY

Man can and does alter the physical environment in such manner to change the thermal regime of the aquatic environment.

He should recognize the effects of these changes and, where possible, their occurrence.

In those instances where alteration of water temperatures is unavoidable, such as might occur by construction of a reservoir, the dam should be designed to permit management of discharges in a manner to minimize adverse thermal effects.

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INDUSTRIAL SOURCES OF THERMAL POLLUTION

I INTRODUCTION

The utilization of water by man is as old as man himself. This life-giving, universal solvent has many uses. It can be used for drinking or to carry away sewage wastes. A river may be used for transportation, recreation, food production (for fish habitat) or for waste disposal. These uses of water for man's benefit may be good but the result is a complex problem.

Competition between water uses is keen and growing intensely with the rapid growth in water demand. It is estimated that the nation's dependable continuous water supply is only 850,000 cubic feet per second, an amount which will be equaled by the demand by 1980. This makes it necessary to manage the resource for multiple use. Antagonistic uses must be resolved to obtain maximum resource benefits.

Heat discharged to a stream conflicts with such other uses, as fish production, domestic use, and recycling as cooling water.

II WASTE HEAT FROM INDUSTRY

A General

There are few industries in the United States that do not to some extent add to the thermal loading on the nation's waterways. Almost one-half of all water used in this country is utilized for cooling and condensing by the power and manufacturing industries. The electric power industry accounts for more than eighty percent of the total cooling water used (Table 1). Although most industry uses water for cooling, not all heat entering the aquatic environment is from cooling water. In many instances process waters contain a thermal pollution load in addition to other contaminants.

B Electrical Power Production

Because the power industry accounts for such a large portion of total cooling water usage, power requirements offer a good correlation to future waste heat loads. Production of electricity has become a more efficient process throughout the years, that is the net heat rate (the number of BTU's needed to generate on KWH) has declined an average of 2.8% per year over the past 40 years. Even with this increase in efficiency, however, total power generation has increased at a net rate of 7.2% annually. That is, doubled every 10 years resulting in greatly expanded cooling water use. Comparatively, manufactured goods production is expected to increase by 4.5% annually over the next few years, and cooling water requirements will increase correspondingly. This rate indicates doubling every 16 years.

Because of a number of factors, heat rejection is expected to increase at least as fast as power production. First of all, fossil-fueled plants are approaching a limit of efficiency, that is, each incremental gain in efficiency is becoming harder to attain. Secondly, the advent of nuclear power will increase heat rejection because of nuclear plants' inherent lower efficiency than fossil-fueled plants. Finally, hydro power will constitute a smaller percentage of the new generating capacity in the future because remaining sites are rapidly being depleted. This is very evident in the Northwest, where the present hydro-base of power will gradually change to a thermal base.

Indications are that waste heat load from power plants, on a national basis, will double before 1980 and probably increase ninefold by the year 2000.

An understanding of the steam cycle may assist in evaluating the problem.

TABLE 1

USE OF COOLING WATER BY U.S. INDUSTRY, 1964

Industry	Cooling Water Intake (Billions of Gallons)	% of Total
Electric Power	40,680	81.3
Primary Metals	3,387	6.8
Chemical and Allied Products	3,120	6.2
Petroleum and Coal Products	1,212	2.4
Paper and Allied Products	607	1.2
Food and Kindred Products	392	0.8
Machinery	164	0.3
Rubber and Plastics	128	0.3
Transportation Equipment	102	0.2
All Other	273	0.5
TOTAL	50,065	100.0

The basic steam plant cycle is as follows: the steam drum furnace combination turns water into high-pressure steam, which is carried to the turbines at a speed of about 200 miles per hour. Within 1/30th of a second the steam rushes through the turbines, traveling through a series of stationary nozzles and revolving buckets which spin the turbine rotor and connected generator shaft at either 1800 or 3600 revolutions per minute.

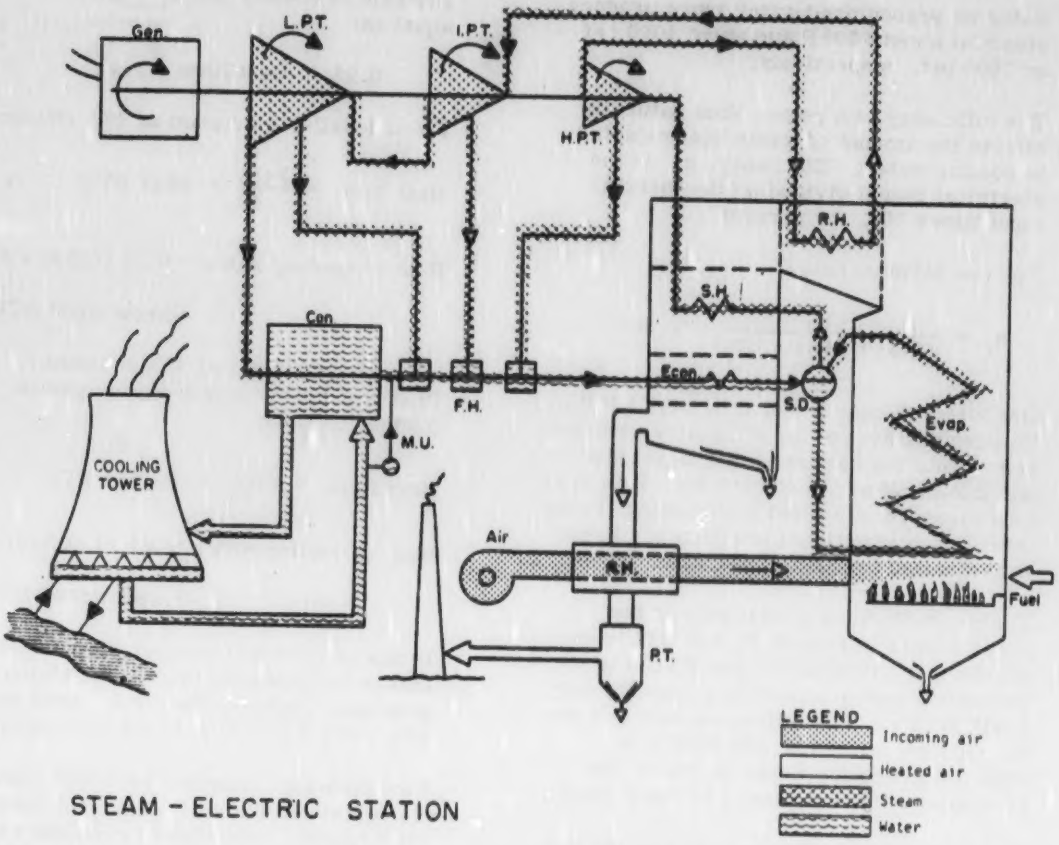
Drastic changes occur in the steam as it releases its energy to the rotating buckets. Steam may enter the turbines at temperatures of over 1000° F and leave at less than 100° F. It enters at a pressure of 2000 or more psi, expands to a thousand times its entrance volume, and leaves at a pressure less than atmospheric.

From the turbine exhaust the expanded, low-pressure steam goes to the condenser, where it is cooled until it condenses to water. The process reduces the volume of the steam by a factor of 27,000 in a near-perfect vacuum, thereby returning it to a state in which it can be easily handled.

The water is returned to the boiler through the feedwater heater to be used over and over again as the cycle continues endlessly.

As the cycle repeats, it is necessary to continuously remove from the condenser an amount of heat equal to that given up in converting exhaust steam into water. Plant and operational refinements reduce the amount of heat entrained in exhaust steam which, in effect, increases the overall plant thermal efficiency.

Nuclear-fueled plants are inherently less efficient than fossil-fueled plants even though they too utilize the basic steam cycle to spin turbines and generate power. The major factor in the efficiency limitation is that imposed through reduced operating temperatures. Technological difficulties make it impractical, uneconomical, or unsafe to produce high-pressure, superheated steam in a water-cooled reactor system. Whereas modern fossil-fueled plants utilize steam at temperatures near 1050° F and pressures over 3000 psi, nuclear-fueled reactors of the boiling



STEAM - ELECTRIC STATION

A.H.	Air Heater
Con.	Condenser
Econ.	Economizer
Evap.	Evaporator
F.H.	Feedwater Heater
Gen.	Generator
H.P.T.	High Pressure Turbine
I.P.T.	Intermediate Pressure Turbine
L.P.T.	Low Pressure Turbine
M.U.	Make-up (water)
P.T.	Electrostatic Precipitator
R.H.	Reheater
S.D.	Steam Drum
S.H.	Super Heater

water or pressurized water types produce steam at about 600° F and about 1000 psi or 2000 psi, respectively.

The efficiency of a power plant naturally affects the amount of waste heat rejected to cooling water. Efficiency, n_t, is the electrical output divided by the thermal input times 100, for percent.

For one kilowatt hour:

$$n_t = \frac{3413}{3413 + \text{Waste Heat}} \times 100$$

One kilowatt-hour is equal to 3413 BTU's. The denominator of the efficiency equation represents the heat required to produce one kilowatt-hour of electricity. It is used as a measure of a plant's efficiency, being inversely proportional to efficiency itself, and is called the plant "heat rate."

The national average heat rate at the present time is around 10,400 BTU's -- which means it takes 10,400 BTU's to generate 1 kwh of electricity equal to only 3,413 BTU's. The difference between the two figures, almost 7,000 BTU's is rejected to cooling water or lost to the atmosphere through plant and stack losses.

The heat rate of even the best present day fossil-fueled plants is about 8,500 BTU's. So we see that, even at best, we must somehow dissipate about 5,000 BTU's of heat for each kwh of electricity we produce.

We can evaluate more closely the amount of heat rejected to cooling water from a plant, knowing the efficiency or heat rate and by assuming some reasonable plant losses. For fossil-fueled plants losses account for about 15% of the thermal input, which is the heat rate. About 10% goes out the stack; 5% is lost within the plant. So the heat that must be rejected to cooling water, per kwh, is equal to:

$$\text{Ht. to CW} = 0.85 \times \text{Heat Rate} - 3413$$

For a nuclear plant, stack losses are not involved and the in-plant losses are taken to be 5% of the input. Therefore, the heat rejected to cooling water, per kwh, is equal to:

$$0.95 \times \text{Heat Rate} - 3413$$

For a fossil-fueled plant at 40% efficiency:

$$\text{Heat Rate} = \frac{3413}{.40} = 8533 \text{ BTU}$$

$$\text{Heat to cooling water} = 0.85\ (8533) - 3413$$

$$= \text{about } 3800 \text{ BTU/KWH}$$

for a nuclear plant at 33% efficiency: (that's about the maximum for plants planned to 1975)

$$\text{Heat Rate} = \frac{3413}{.33} = 10,340 \text{ BTU}$$

$$\text{Heat to cooling water} = 0.95\ (10,340) - 3413$$

$$= \text{about } 6400 \text{ BTU/KWH}$$

It can be seen that nuclear plants will not lessen the potential thermal pollution problem. Instead, they will reject about 65% more waste heat to cooling water.

For example, consider 1000 MW plants. As calculated for a 40% efficient fossil-fueled plant, waste heat to cooling water is about 3800 BTU/KWH. For a 1000 MW plant, the total heat output would then be 3.8×10^9 BTU/hr. Such a plant might circulate 1000 cfs through it. (= to stream 20 ft wide, 10 ft deep, running at 5 ft/sec). The temperature of this 1000 cfs would be raised 17° F through the 1000 MW fossil-fueled plant.

Heat from a 1000 MW nuclear-fueled plant would be 6.4×10^9 BTU/hr. If, for comparison, we want a 17° F temperature rise through this plant also, it would require a cooling water flow of 1650 cfs.

The following relationship can be used to determine a heat load (H_L) streamflow (S_f), or temperature (ΔT) rise if values are known for 2 of the 3 factors.

$$\Delta T = \frac{H_L}{S_f \times 62.4}$$

where: ΔT = change in stream water temperature, ^{o}F

H_L = heat load in BTU/sec and

S_f = streamflow in cubic feet per second

62.4 = Wt. of water, lb/cu.ft.

C Manufacturing Industries

As shown in Table 1, about 80% of all industrial cooling water is used by the power industry, and the remaining 20% by manufacturing industries. Manufacturer's cooling facility needs are expected to increase at a 4.5% annual rate, compared to the 7.2% annual increase expected by the power industry.

To assess the impact of an industry or an industrial complex on the thermal properties of a stream, one must determine the quantity of waste heat, i.e., total BTU's, discharged from each plant. Specific values of heat wasted by various processes are generally not applicable to individual plants, due to the wide range of production processes, equipment combinations, and efficiencies employed. Therefore, no attempt to formulate quantitative guidelines will be made here. Rather, it is suggested that the situation be approached through studying each manufacturing plant's discharge and sources of heat additions both to process waters and cooling water streams. In this manner, incorrect assumptions will not be used and a more valid heat load determination will be assured.

ACKNOWLEDGMENT:

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BIOLOGICAL MONITORING OF HEATED LAKES AND STREAMS

I INTRODUCTION

A Laboratory conditions usually include constant temperatures, closed systems, and feeding of test organisms. Natural environments are anything but constant.

1 Lakes stratify in summer and produce marked thermal gradients.

2 Streams have springs and impounded areas which provide for contrast in temperatures, and heated water discharges have mixing zones which have sharp isotherms.

3 Fish have a choice to select water favorable for their growth and survival.

4 Natural waters must also produce suitable food organisms and fish must compete with other species, as well as their own, for the available food resources.

B The relationship between growth, mortality, reproduction, and behavior is anything but constant.

1 Fluctuations in abundance may vary more than 25 fold from year to year (Smith and Krofting, 1954).

2 Survival of white fish eggs to maturity has been estimated to be only about 0.03% on the average (Braum, 1967).

3 Growth rates generally show an inverse relationship to population size.

a Fishermen usually know about lakes where the fish are quite stunted and numerous, and other lakes where fish grow to a large size but are not so numerous.

b Although the number of fish present are highly variable from year to year, or from lake to lake, the tendency is for the loss of numbers to be compensated for by increase in weight. Thus, the pound of fish flesh produced per acre per year tends to be constant for any body of water much the same as an agricultural crop.

4 Variations in production rates are related to the fertility of the watershed and to the temperature.

a Serious loss of production rates can be expected at abnormal temperatures when the compensatory mechanisms are no longer effective to make up for the loss in numbers from reduced reproduction, increased mortality, and avoidance of large areas of food producing waters.

5 Because of the complexity of the problem of heated waters, there is a strong need for testing laboratory findings in the field to determine their adequacy for the protection of aquatic life.

II LIMNOLOGICAL CONSIDERATIONS

A In any river or stream in which a flow of water is maintained, the continual mixing of water prevents the establishment of a thermal stratification such as found in lakes.

1 Heat discharges to shallow turbulent streams will result in complete mixing with the receiving water raising its temperature before being cooled by evaporation.

2 The entire water mass will influence the distribution of organisms, since little temperature differences occur.

B Addition of heat to the surface of lakes and slow, deep streams will result in thermal stratification.

1 These discharges may have no significant effect on the adult population living in deeper water.

2 Larval fishes living in surface waters may be adversely affected.

C Report of the committee on Water Quality Criteria (1968) recommends that the hypolimnion of lakes should not be warmed or used for cooling waters.

1 Such use of the cold water layer may cause a decrease in its volume, increase in volume of the warm surface layer, prolong the period of stratification and the growing season, decrease its oxygen concentration, and decrease the living space of cold-water fishes (Eipper, et al, 1968).

2 Documentation of these predicted biological changes is needed for both cold - and warm - water organisms.

D The type of discharge which may be surface or bottom, on shore or off shore; the temperature at various loads, flow conditions, and seasons; and the flow rate of the discharge will ultimately generate isotherms that will have varying effects upon the aquatic environment.

1 Some areas may not be habitable during parts of the year.

2 Only a small fraction of the total environment, however, may actually be utilized by any life history phase of a fish at any time of the year.

3 It is important that these requirements for specific isotherms are recognized and that sufficient "living space" is available to insure adequate production of the desired species.

4 Engineers try to predict the isotherms generated under various conditions and it should be the biologist's goal to be able to predict the consequences of such isotherms, to recommend changes in heat distribution, and to suggest areas to be monitored and for site selection.

III ECOLOGICAL CONSIDERATIONS

A One of the more important ecological considerations is the relationship of the desired organisms to their food supply.

1 Fishes are among the first group of animals to disappear from the environment and the algae and food organisms are among the last.

2 One of the most heat tolerant fish, the goldfish, dies at 40° C.

3 (Wurtz and Renn, 1965), observed 19 macroinvertebrate species which survived temperatures up to 41° C in a Pennsylvania stream.

4 TVA (1968) reports that zooplankton were extremely abundant at 35° C, but 36° C represents the lethal threshold for the dominant species of the Green River.

5 A 50% reduction in the number of species of macroinvertebrate fauna of the Delaware River occurred at a temperature of 34° C (Coutant, 1962).

B These observations are consistent with principles of toxicology; the greater the number of species within a group of organisms, the greater their range of tolerance.

1 One could logically argue that survival of fish is the most critical factor and that ample food would be available, if criteria are set for fish alone.

2 Most species of fishes will alter their food habits considerably depending on what type is available.

C The dependency of a population of fish on a single food organism has not been demonstrated until recently.

1 (Swedburg, 1968) found that the increased growth and abundance of the freshwater drum in Lewis and Clark Lake was related to an increased abundance of its preferred food, the burrowing mayfly (Hexagenia).

2 Food that newly hatched fry can eat are much more restricted than the types available to a larger fish of the same species (Siefert, 1968).

3 The preferred food organisms, especially the food of fish fry, must be protected in order to raise a crop of fish.

4 The effect of heated waters on these food organisms must be taken into consideration in order to evaluate changes in fish production.

D Another important consideration is the timing of life cycle events.

1 Each organism is adapted to not only water temperature, but to other factors such as day length and other species of animals and plants in the same habitat.

2 The interrelationships of species, day-length, and water temperature are so intimate that abnormal temperature cycles may have adverse effects.

3 The temperature cycle must be in phase with the light cycle or reproduction will be inhibited.

4 A stonefly nymph reared under a constant high temperature of 20° C emerged in January, but emerged in May at normal temperatures. The air temperature can reach -20° F in Minnesota in the winter. It doesn't have to be emphasized that the mating of this insect would be impaired at that temperature.

5 It could well be that other organisms will suffice as the missing link in the food chain, but this relationship must be studied.

E Different zooplankers have different cycles of abundance depending on the differential effect of several factors, including water temperature.

1 These cycles of abundance are very important for the survival of first-feeding fish fry.

2 The availability of the right species of food organism of the right size (age) in sufficient numbers must exist at the time when the fry begin to feed.

3 There would be no survival advantage in having abundant adults, since they are too large.

4 The period when bluegill fry begin to feed and when they starve to death is only two days at 23° C (Toetz, 1966) and this period is shortened at higher temperatures.

5 Whether adequate food will be available to these fry at higher temperatures is a matter of speculation that needs critical examination.

6 So important is this relationship that success of reproduction for most fish species is usually determined within the first month of life even at normal temperatures.

F The effect of water temperature on development of fish diseases is another area of research that needs considerable attention.

1 Laboratory and field observations indicate that many fish diseases are favored by increased water temperatures.

a Columnaris infections of salmon migrating in the Columbia River system reached epidemic proportions only at temperatures in excess of 21° C (Ordal and Pacha, 1963).

b Increased water temperatures in the main Columbia River in 1957 and 1958 contributed to the increased incidence of columnaris disease and reduced the salmon run into Redfish Lake in Idaho.

2 Increased water temperatures are the combined results of the chain of impoundments on the Columbia River system and warm seasons.

a Warm-water discharges which attract infected warm-water fishes aid the over winter survival of this disease.

b Closer examination of the thermal requirements of this fish, the sockeye salmon, shows that the ultimate lethal temperature is 24° C (Brett, 1952) while the temperature of maximum activity and growth is about 18° C (Brett, 1960).

3 Apparently, survival at temperatures above the optimum temperature range of a fish is conditional, making the concept of lethal temperatures more nebulous.

G It should be emphasized that high natural mortality rates occur in nature and the role of diseases in regulating populations under stress is well known.

1 Fish diseases are common in over-crowded populations or in starving populations (Wohlschlag and Juliano, 1959).

2 Mortalities from diseases are common in fishes, when water temperatures rise rapidly in the spring (Davis, 1922).

3 This is related to the period when resistance of fishes to diseases is at its lowest level (Liebmann, et al, 1960).

4 Fish collected below domestic waste discharges in the Mississippi River were all diseased.

5 The stress of laboratory confinement, such as handling, crowding, accumulation of excess food and waste products, are all known to be contributing to disease.

6 It was found that the only way to keep yellow perch alive and healthy at temperatures in excess of their optimum of final preferred temperature range was by routine treatment with fungicides, bactericides, and antibiotics.

H High temperatures are known to increase the toxicity of several wastes to aquatic life.

1 As a general rule, the survival time of an organism in a lethal concentration decreases by a factor of 2 to 3 for a temperature increase of 10° C (Lloyd and Herbert, 1962).

2 Even the dissolved oxygen requirements of fish is a function of temperature.

a The minimum concentration of dissolved oxygen survived by bluegill sunfish for 24 hours was 0.8 mgl at 25° C.

b It was 1.2 mgl at 35° C (Moss and Scott, 1961).

3 The differences in the preferred temperatures of young and adult fishes may be explained by the differences in the efficiency of their respiratory mechanisms.

a Larger fish have a relatively smaller surface area of their gills (Price, 1931; Saunders, 1962) and are less efficient than the young in extracting the limited amounts of oxygen available at higher temperatures.

b It can be argued that larger fish seek cooler waters then their young in order to maximize the efficiency of respiration even though they have similar lethal temperatures.

I Several species of aquatic life occur naturally together in each body of water. Where there is competition with other ecologically similar species, the range of habitat conditions which the species occupies generally becomes restricted to the most favorable conditions where the species has an advantage over its competitors (the optimum temperature range).

1 The different thermal requirements of fish may result in spatial separation of the species whereby they never come into association with one another. When requirements are similar, competition becomes more severe.

2 In Quebec, introduction of yellow perch into lakes has resulted in severe competition with brook trout.

3 This is attributed in part to their similar thermal thermal requirements and food habits and is aggravated by the higher reproductive potential of perch.

J In streams where temperatures are more uniform, changes in species composition takes place as one proceeds downstream. Numerous examples exist of the ecological succession of cold-water species in the headwaters to the warm-water species near the mouth.

1 If any appreciable heat load is introduced into a stream, the species composition will be shifted towards the one of a more southerly water.

2 The warm-water species are more active, grow faster, and consume greater amounts of food, while the cold-water species are less active, less efficient in converting food into growth, have lower survival of their young, and are vulnerable to diseases and other adverse conditions.

3 The change in species can take place without any spectacular fish kills.

a Whether these changes are detrimental or beneficial depends on what species you are trying to protect.

b Thermal requirements for a desired species, therefore, must consider the requirements of the other species which may become dominant through slight changes in environmental temperatures.

K The natural downstream movement of planktonic organisms and of aquatic invertebrates in streams are important factors in the re-population of areas below heated discharges and are part of the production dynamics.

1 The young of many fish species may be part of this stream drift during short periods of the year and are vulnerable to entrainment into cooling water intakes.

2 Spawning migrations of several fish species occur during portions of the year.

a It is essential, therefore, to provide adequate passageways for the movement or drift of these organisms, especially during the critical periods of the year.

L Survival of organisms in the mixing zone depends on several factors; the pattern of dispersion of heated water, the heat and cold tolerance of each species which varies with their environmental temperature history, the temperatures of the heated discharge and the receiving water, and the rate of change in temperatures. The pattern of heat discharge determines the thermal gradient to which organisms are expressed.

1 Some fish cannot avoid sharp gradients and are killed when they swim into lethal temperatures (Van Bliet, 1956).

2 Fast rates of change in heated discharge temperatures do not have any appreciable effect on the lethal temperatures of several species of fish (Trembley, 1960); (Cocking, 1959); and aquatic invertebrates.

3 Slow rates of change on the order of 1° C per day may alter their lethal temperatures by influencing the rate of gain in heat and cold tolerance.

4 In general, sharp thermal gradients and large increments of heat above ambient water temperatures should

be avoided especially in winter, when fish are attracted to these areas.

a If the heated effluent raises the cold tolerance (acclimation) of the most sensitive species above the receiving water temperature, kills may be expected when the supply of warm water is interrupted or when they move into the receiving water.

b Similarly, the effluent should not exceed the heat tolerance of fish acclimated to the cooler receiving waters.

IV SUMMARY

A Water pollution must be defined in the context of water use.

1 The first job, therefore, is to decide what the water should be used for.

2 If the general public decides that protection of aquatic life should be given high priority, then they must decide what species should be protected.

B The thermal requirements for each species is different and no single temperature will protect a species throughout the year on all age groups of the same species.

1 These organisms have adapted to an environment where natural thermal gradients exist and where daily and seasonal temperature fluctuations occur.

2 Until further research shows otherwise, it is important that these gradients and cycles be maintained.

C Current thinking on the thermal criteria for aquatic life is that each species has a seasonal maximum temperature which must not be exceeded.

1 This is to insure successful completion of all life history phases.

2 A portion of the year is devoted to maturation of eggs of fish.

3 Two weeks to two months may be devoted to complex spawning behavior, another portion of the year is devoted to incubation of the eggs and the remaining portion of the year concerns growth and well being of both the young and adults.

4 Adding a constant temperature increment above surface water temperatures would have different effects depending upon whether it is a cold or warm season and if it is in the northern or southern part of the range of a species.

5 A more realistic approach is to set seasonal maxima for each desired species.

6 More flexibility can be afforded by recognizing monthly, daily, and hourly requirements of these organisms.

D It is recognized that mixing zones are inevitable for any waste discharge. But it is important that large increments of heat with sharp thermal gradients be avoided to prevent fish kills.

1 Zones of passage for the downstream drift and movement of migratory species should be provided.

2 It is also important that the seasonal maximum temperature should be confined to some minimum area near the discharge to provide "living space" for the desired species.

3 It is hoped that seasonal maximums will be set for desired organisms and that realistic limits will be imposed on isotherms generated from heated discharges.

E Temperature criteria are the most difficult to determine, since temperature has an incluence on every conceivable function and activity of aquatic organisms.

1 Any change in temperature will bring about changes in the environment.

2 These changes are brought about by subtle effects of temperature on reproduction, growth, and behavior of each species and through complex interactions with their environment.

3 Dramatic fish kills are only of secondary importance.

F These changes can be detrimental or beneficial.

ACKNOWLEDGMENT:

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DATA REQUIREMENTS, FIELD STUDIES, AND INSTRUMENTATION FOR TEMPERATURE PREDICTION

I INTRODUCTION

Some simple basic equations which can be used to predict temperatures with certain simplifying assumptions have been developed. The following discussion concerns methods for acquiring the physical data necessary to the solution of these equations.

The first thing to be done in any situation is to learn if any data are already available and if it is suitable for the intended purpose. Two basic types of data are required--hydrologic and meterologic.

Two good sources for hydrologic information are the U.S. Geological Survey and the Corps of Engineers. Meteorologic information is available from the U.S. Weather Bureau and the Federal Aviation Agency. These four Federal agencies would be the first to contact although many other sources might be available.

II DATA REQUIREMENTS

In order to assess the data required, each situation must be examined independently.

A Example Problem

A 1000 megawatt electric output nuclear power plant is to be located on a well-mixed river. The problem is to determine the effect this plant will have on downstream temperatures.

1 Assume there is not adequate Weather Bureau data available, and the information necessary to solve the basic stream temperature prediction equations developed earlier must be collected. Further assume major interest is in summer (June-September) temperatures, and the study must be completed in only one summer. Adequate hydrologic data is available, so only meteorological data will be obtained. Since only one summer's data can be collected, it will be necessary to rely on comparisons with past regional weather data to determine whether this one summer was average or whether it was hotter or colder than average. Extreme conditions will be estimated from the collected data and its relationship to past regional data.

2 Under the circumstances described, it would be necessary to do a fairly intensive survey of relevant meteorological conditions at the site, plus acquiring river temperatures at several points down-stream. Recorders should be used as much as possible in order to obtain continuous records of variations in the measured parameters.

3 What data should be obtained? This question may be answered by examining the basic equations.

a Energy exchange coefficient

$$K = 15.7 + (0.26 + B)\, bw$$

b Equilibrium temperature

$$E + \frac{0.051\, E^2}{K} = \frac{H_R - 1801}{K} + \frac{K - 15.7}{K}$$

$$\frac{e_a - C\,(\beta)}{0.26 + \beta} + \frac{0.26\, T_a}{0.26 + \beta}$$

c Stream temperature

$$T_x = (T_o - E)_e \quad \alpha X + E = \frac{-K}{pC_{py}U}$$

4 The following physical variables are required to solve the preceding equations:

a Wind speed (w)

b Net radiation input (H_R)

c Vapor pressure of ambient air (e_a)

d Air temperature (T_a)

e Water temperature (T_o)

f Stream depth (y)

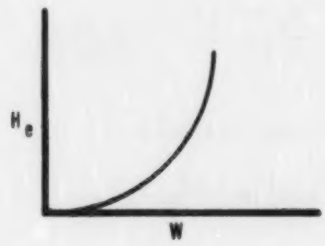
g Stream velocity (U)

III INSTRUMENTATION

Methods used to collect data will be considered. Comments will be restricted to the operation and design of the sensing elements of the instruments, and will not include methods of recording the information. Whenever an electrical signal or mechanical motion is an output, automatic recording can be achieved. The need for recording the data on a continuous basis depends on the type of study to be conducted, but should be practiced if at all possible.

A Wind Speed

Wind speed is one of the most critical meteorological variables in water temperature studies. As can be seen, wind speed is the only variable which affects K. It is sensitive to location, and care is necessary to assure an unobstructed air flow past the sensing device. In addition, the height above the ground or water surface at which the wind is measured is important.



A profile of wind speed near the ground is an exponential type curve (Figure 1) which, if plotted on semilog paper, would be linear. This type of profile exists within the turbulent boundary layer which may extend from 50 to several hundred feet above the surface of the earth. Thus, at any location, several different readings for wind speed could be obtained depending on the height at which it was measured. This fact is evident when one examines the various experimental equations for evaporation of the form:

$$H_e = bw\,(e_s - e_a) \text{ or } H_e = bW_z\,(e_s - e_a)$$

The z subscript indicates the height at which the wind and vapor pressure were measured.

Several types of anemometers are available. These include cup type, fan or blade type, pressure-tube, and hot-wire. The most common is the 3-cup type, which has a starting speed of less than two miles per hour, depending on the inertia of the cups. More sensitive units use light weight plastic cups to reduce inertia.

A fan type wind speed indicator such as a Biram anemometer is useful for making spot checks of wind speed.

B Net Radiation Input

Net radiation input is equal to incoming short-wave solar radiation plus atmospheric long-wave radiation minus reflected short-wave radiation minus reflected atmospheric radiation.

1 Solar radiation

Incoming solar short-wave radiation can be computed, but the calculations require several empirical coefficients. Therefore, it is usually measured.

a The instrument used to measure direct solar radiation at normal incidence is called a pyrheliometer. These instruments are mounted so as to always be directly facing the sun.

b Instruments which are used to measure solar radiation (including scattered) from the whole hemishere are called pyranometers. These instruments are placed so their detecting surfaces are level and they measure the solar radiation at all angles as the sun passes over. Since they are used to measure all 180° of the sun's radiation they are often called 180° pyrheliometers.

From a variety of available pyranometers, two of the most common are the Eppley type and Moll-Gorczynski type.

1) Eppley

- 2 concentric silver rings
- one white, one black
- temperature difference proportional to solar radiation intensity
- thermocouple junctions give voltage output
- a 50 junction model which is more sensitive than the 10 junction model

2) Kipp and Zonen solimeter

- flat black surface (to permit uniform absorption of long and short-wave) thermopile consisting of 14 thermo-couples
- both units give voltage output proportional to cal/cm^2 min.

c Care must be taken to place the pyranometer in a location where it will not be obstructed by shade. The glass which covers the units acts as a wavelength screen so that only short-wave radiation can reach the detecting surfaces.

C Atmospheric Long-Wave Radiation

This cannot be measured directly, except at night in the absence of solar radiation, and can be calculated only to within 10 to 20% of the actual value.

D Reflected Short-Wave Radiation

This could be measured by using a pyranometer point downward towards the water surface, but this is not usually done. It can be calculated from a knowledge of sun altitude, cloud height, and cloud cover. Sun altitude can be taken from a solar ephmeris and cloud height and cover are usually "eyeball" estimates. Empirical relationships are then used to compute short-wave reflectivity.

E Reflected Long-Wave Radiation

This cannot be measured directly, except at night, but it is estimated to be about 3% of the incoming long-wave radiation.

F Net Long-Wave and Short-Wave Radiation

Instruments are available which can measure the net radiation through a horizontal surface. These are pyrradiometers and the two most common types are the Gier and Dunkle flat plate radiometer and the Thornthwaite miniature net radiometer.

1 The Gier and Dunkle radiometer uses a thermopile (groups of thermocouples) in the form of a flat plate which is mounted on the end of a blower tube to maintain air flow over both sides of the plate. This prevents unequal convection currents from developing on either side of the plate. The thermopile indicates the temperature difference between the top and bottom of the plate which is proportional to the net radiation.

2 The Thornthwaite miniature net radiometer consists of a thermopile which measures the temperatures of both sides of a black disc. The disc is covered on top and bottom by hemispheres of clear polyethylene which is transparent to all relevant wavelengths and has a low absorption. The pressure inside the hemisphere is about 2 psi and the air is dried before being inserted into the space to prevent moisture from entering the area.

These meters measure both the net radiation input (H_R) and the back radiation (H_{br}). Therefore, H_R is computed by subtracting H_{br} from the net radiation.

3 Another device which is used to measure net radiation is a Cummings Radiation Integrator. This device is merely an isolated pan of water on which energy budget calculations are performed. There are no set sizes, although 4 foot diameters and 20 inch depths are common. They are placed so as to be exposed to the same radiation conditions as the water body, but are usually sheltered from the wind to minimize evaporative and conductive-convective heat exchange. Water removed by evaporation is replaced as often as possible to maintain a constant mass. Temperature measurements are made in the pan, and the change in water temperature over a period of time indicates the total energy change. Since evaporative loss is known, convective exchange can be reasonably estimated via the Bowen Ration. Back radiation can also be easily computed and thus the remaining energy change is due to radiation. U.S.G.S. experiences with these units at both Lake Hefner and Lake Mead have been favorable. (Measurements needed: wet and dry bulb air temperature, water temperature, barometric pressure, and precipitation temperature).

G Vapor Pressure of Ambient Air (e_a)

The pressure of the water vapor in the air (e_a) can be computed by multiplying the relative humidity by the pressure of saturated water vapor in the air at the same temperature:

$$e_a = (\text{r.h.})\ (e_{sat} \ @\ T_a)$$

e_{sat} is a constant for any air temperature and can be found in published psychrometric tables and other standard references (i.e., Handbook of Chemistry and Physics).

1 The relative humidity can be computed from the air temperature and either the wet-bulb or dew-point temperature.

2 The wet-bulb temperature of the air is found by passing an air stream over a wetted temperature sensing element. The latent heat lost by evaporation will lower the temperature of the sensing element until a heat balance is obtained. This steady state temperature is the wet-bulb temperature.

a The sling psychrometer is the type most often used. Fan aspirated psychrometers are becoming more popular. The Assmann type employs mercury thermometers and a spring wound fan motor.

3 Dew-point determinations are made with two basic types of units. One type employs a shiny surface which at the dew-point will cloud up. Electronic units are available for this type which uses changes in the character of the light reflected from the surface to record dew-points. Another type of dew-point detector uses a chemical compound such as lithium chloride which changes its electrical resistance under different moisture conditions. When this material becomes saturated the resistance will be constant, and the dew-point is indicated.

Regardless of whether dew-point or wet-bulb readings are used, they should be taken at the same height above the water surface as the wind speed.

4 Relative humidity (or e_a) can be determined with a wet-bulb temperature (and associated dry-bulb temperature) or a dew-point temperature.

a Tables are available which relate the difference in air temperature and wet-bulb temperature (called wet-bulb depression) to relative humidity as a function of air temperature. The barometric pressure of the atmosphere also has a slight effect, and this is taken care of in the tables. (The higher the barometric pressure at a given wet-bulb depression the lower the relative humidity).

b e_a can be directly obtained from dew-point measurements. The dew-point is the temperature at which the water vapor in the air becomes saturated. Therefore merely by looking up the saturated water vapor pressure at the dew-point will provide e_a.

c Instruments called hygrometers are available for directly measuring relative humidity. These instruments use sensing elements, such as hair or animal membranes, which expand and contract with changes in moisture content. High quality hygrometers are reasonably accurate at moderate temperatures and between relative humidities of 30 to 80%. At low temperatures and at relative humidities outside these limits, the accuracy of hygrometers falls off.

H Air Temperature

1 Dry-bulb air temperature measurements should be made at the same level as wind speed and wet-bulb or dew-point determinations. Care must be taken not to expose the sensing element to direct sunlight, and some air movement is also desirable.

2 There are a variety of ways to measure temperature, including:

a Mercury or alcohol filled glass thermometer

b Bi-metallic deflection type (like on a home furnace thermostat)

c Gas or liquid filled systems with Bourdon tubes

d Electrical types

- Thermocouples--junction of 2 dissimilar metals which generates a voltage when there is a temperature difference.
- Thermistors--semi-conductor materials whose electrical resistance varies with temperature.
- Resistance Thermometers--metallic materials whose resistance varies with temperature.

I Water Temperature (T_o)

1 For complex hydraulic situations with spacial temperature variations, care must be taken to position water temperature sensors in such a manner as to adequately describe the temperature regime. In a well-mixed water body, there is, by definition, no spacial variation in temperature, so the location of the sensing element is less critical. One factor which should be recognized is that the water temperature dependent heat exchange components of the energy budget are related to the surface water temperature. It is usually difficult to determine the temperature of the very thin top layer; however, it is normally assumed that a foot below the surface is adequate.

For the example problem, II-A, the river temperature would be continuously monitored at one point above the proposed site, at the site, and at several points below the plant. The spacing of the measuring points would depend on the time interval for which predictions are required and on the speed of the river. Any influent streams or downstream discharges from the plant would also require monitoring. The downstream temperatures will be used to check temperature predictions made for natural conditions, and can also be used as checks in the future to note changes from the river's natural thermal regime.

2 Basically, the same type of instruments are used for water temperature measurements as for air temperature determinations. However, water temperatures need to be measured at some distance from the indicating mechanism; therefore a connecting cable or tubing is required.

   a The Whitney Underwater Thermometer is a very precise and accurate instrument. This model has a range of 0-40° C in eight 5° C stages. The instrument is very rugged and is specifically designed for field application. Cables of up to 1000 ft. can be ordered. Cables are marked at regular intervals for easy reading. The unit is especially useful for lake surveys.

   b In the Foxboro liquid filled thermograph, the liquid changes its volume as the water temperature changes and a Bourdon tube actuates the pen. The unit is temperature compensated so the temperature inside the case will not affect the readings. The chart is driven by a spring wound motor. This unit has a temperature range of 30-90° F.

   c These are only two of the many different types of equipment which can be used to measure water temperature. Most water temperature measurements are made by immersing the sensing element. However, remote sensing equipment is also available. Since water emits back body radiation at a rate proportional to the fourth power of the surface temperature, this back radiation can be used to determine surface temperatures. The past few years has seen the development of remote radiometers which are used to perform this function. Operated from airplanes, or even orbiting satellites, these devices can give an aerial picture of a water body's surface temperature. Such remote scanners are especially valuable for synoptic surveys over large distances.

J Stream Depth and Velocity

Hydrologic data and maps can be used to acquire this data. Stream velocity can be simply computed by $V = Q/A$.

K Remote Sensing of Thermal Pollution

Most outstanding of the work already done on the use of remote sensing techniques to determine the discharge and spread of heated waters has been the use of the NIMBUS satellite high resolution infrared imagery to detect contours of the Great Lakes (National Council on Marine Resources, 1967). Though some of the needed information in this area is still classified, sufficient data is known to enable one to use the technique and its airplane and laboratory versions to study the patterns of temperature distribution on water surfaces.

1 A number of commercial firms are available on a contract basis to provide complete service. Infrared wavelengths, in the 1.5 to 14 micron range are used in hydrologic studies because in this region the infrared energy emitted by land and water bodies is at a maximum and atmospheric absorption is at a minimum (Lukens, 1968). A typical scanner is sensitive to 1/4° C surface temperature changes and can be calibrated with surface instrumentation to 1/2° C.

2 A brief evaluation of the use of remote sensors in hydrology was presented at the International Conference on Water for Peace (Robinove, 1967). At that time, photographic sensors were still most favored because of the easy interpretability and the minimum data reduction and specialized training needed for their use. Infrared sensors offer hope of great things in thermal pollution work, but are hampered in a quantitative - not qualitative - sense at present by problems of emissivity measurement. In any case, infrared imagery is only a function of the surface temperature of the waters and does not give any indication of the thermal profile.

III CONCLUSION

The type of study will normally dictate the accuracy required of the data and this in turn will dictate the quality of the instruments required. It would be costly to buy extremely accurate instruments designed for sophisticated scientific studies if they were to be used only on preliminary surveys. On the other hand, trying to skimp on instruments can leave one with poor quality data which may be useless for its intended purpose. No hard and fast rules can be applied to equipment selection, but an evaluation of the potential uses of the instrument is necessary before a choice is made. Finally, a recorder should be as good as the instrument with which it will be used. A poor recorder will give questionable data no matter how good the measuring instrument.

With respect to cost, a complete meteorological setup of reasonably high quality would run about $4,000. A water temperature recorder would add to this figure.

ACKNOWLEDGMENT:

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This outline was prepared by James A. Montgomery, Sanitary Engineer, River Basin Planning, OWP, EPA, Washington, DC 20242.

SUMMARY OUTLINE OF CURRENT THEORIES RELATING TO TEMPERATURE PREDICTION IN A BODY OF WATER

I INTRODUCTION

A The causes, effects, and methods of controlling thermal pollution have been discussed. The following analytical tools may be used to determine the physical impact of a potential thermal pollution source.

B The ability of the engineer working for regulatory agencies to accurately predict water temperatures is necessary in order to determine the thermal impact of:

1 Proposed waste heat discharges

2 Changes in the hydraulic characteristics of a water body or stream -- for example, due to dam construction

3 Releases of water from stratified reservoirs with multi-level outlets

4 Unusual meteorological conditions

In short, there is a need to be able to predict water temperature effects of any natural or man-caused phenomenon which may alter the hydrologic or meteorologic regime.

II THE ENERGY-BUDGET APPROACH

A The energy budget attempts to equate the net exchange of heat between a body of water and its environment to changes in water temperature. Energy-exchange processes normally considered include (Notations from Schroepfer):

1 The difference between incident and reflected solar radiation $(+\Delta T_s)$

2 The difference between incident and reflected atmospheric radiation and the loss of heat by thermal radiation from the water surface (i.e., net exchange of long-wave radiation) $(-\Delta T_R)$

3 The loss of heat due to evaporative processes $(-\Delta T_E)$

4 The gain or loss of heat due to temperature difference at the air-water interface $\pm(\Delta T_c)$

5 The heat gain due to discharge, for example, of cooling water into the reach $(+\Delta T_A)$

B These incremental temperatures, then, are added algebraically to the upstream temperature, T_A, to estimate the downstream interface temperature, T_B, as follows:

$$T_A + \Delta T_A + \Delta T_S - \Delta T_E \pm \Delta T_c - \Delta T_R = T_B$$

Other processes actually involved, but usually disregarded, are biochemical reactions and conduction of heat at the water-channel bottom interface.

Since computation of evaporation and thermal radiation exchange depend on the assumed downstream temperature, the equation cannot be solved directly. Formulae, such as the above, can be solved by successive trials assuming downstream temperatures, T_B.

C This method is used, equally well on streams in their natural, steady-state condition as on streams receiving large amounts of cooling water or cold, reservoir water.

For detailed descriptions of theory and data relative to individual energy-budget parameters, the interested reader is referred to several references in the bibliography (1, 6, 7, 8, 17).

III EQUILIBRIUM TEMPERATURES AND EXPONENTIAL DECAY OF TEMPERATURE INCREMENTS

This second approach is a two-fold operation.

A First, the steady-state, or equilibrium, temperature of the water is estimated by any one of several methods.

1 Energy-budget equations, as just discussed

2 Simple correlation with air temperature as Gameson, Hall and Preddy did on the Thames Estuary in 1957

e.g., The Thames Estuary data yielded the following relationship:

Equilibrium Temperature =

$$\theta = 0.5 + 1.109\,T_a$$

3 Estimation of the natural stream temperature according to its response to its thermal environment as expressed by Duttweiler's equations: Heat input =

$$T_\varepsilon(t) = \frac{Q_n - 25}{\lambda} + \frac{B_1 T_{ad} + C_B T_a}{B_1 + C_B}\,\frac{(\lambda - \frac{1}{2})}{\lambda}$$

$T_\varepsilon(t)$ = input temperature

$Q_n - 25$ = net radiation input

B_1 = slope of saturation vapor pressure vs. air temperature curve

T_{ad} = dewpoint temperature

C_B = bowen ratio coefficient (0.61)

T_a = air temperature

λ = heat exchange coefficient

Water temperature =

$$T(x,t) = T_m + \sum_{n=1}^{\alpha} T_{un} \sin(n\omega t + \phi_n - \alpha n)$$

T (x, t) = water temperature with distance and time

T_m = mean temperature with time

= infinity

u = absolute maximum and minimum value of water temperature

n = number of cycles

ω = $\pi/12$

t = time in hours

ϕ = arctan A_n/B_n where A and B are coordinates of the Amplitude Point

α = lag factor-arctan n /k

k = rate constant

The first of these equations is plotted from a knowledge of climatological data. Short time intervals will yield points on a modified sine curve.

The second equation is merely a reflection of the first modified by an amplification factor (T_u/T_1) and phase lag (α).

B Second, transient temperatures due to thermal additions are decayed exponentially downstream.

Regardless of what form the equilibrium temperature takes, transients can be accounted for by computing the initial temperature increment and reducing it exponentially downstream. The exponential decay factor can be expressed as follows:

$$e^{-\frac{k}{v^{x}}}$$

Thus: $\Delta T_1 = \Delta T_0 e^{-\frac{k}{v}x}$

Where: v = average velocity

x = dist. downstream

And: k has been evaluated by Major Duttweiler as $\frac{\lambda}{z}$

Where: z = average depth

And: $\lambda = C_1 + C_2 U_2 = 1.35 + 0.2\ U_2$

Where: U_2 = estimated wind speed in mph

ACKNOWLEDGMENT:

Materials for this outline were taken from "Summary of Current Theories and Studies Relating to Temperature Prediction." 12th Pacific Northwest Symposium on Water Pollution Research. Water Temperature, Influence, Effects and Control manual. Presentation by Robert Zeller.

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DISSIPATION OF HEAT IN A BODY OF WATER

I INTRODUCTION

Obviously, the simplest method of disposing of waste heat is to discharge it directly to the receiving water and then allow natural forces to bring the water back to an equilibrium temperature. In order to predict the behavior of these heated effluents, it is necessary to resort to an energy balance.

Much of the work on the heat balance has been primarily concerned with the prediction of evaporation rates. A brief presentation of completed studies will be made. For a more extensive literature review of this subject, the reader is referred to references (2, 15, 55 and 57) listed in the Water Temperature and Prediction Bibliography placed at the end of this section of the training manual.

II THE BALANCE OF ENERGY

A The use of the energy budget approach for estimating evaporation has been applied to compute evaporation from water bodies of all sizes. The relatively recent development of more sophisticated instrumentation has allowed the energy budget approach to be utilized with a fair degree of reliance.

1 The components of the energy budget per unit surface area of a reservoir per unit time may be written as follows (World Meteorological Organization, 1966):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q \quad \text{Eq. 1}$$

where:

Q_s = short-wave radiations incident to the water surface

Q_r = reflected short-wave radiation

Q_a = incoming long-wave radiation from the atmosphere

Q_{ar} = reflected long-wave radiation

Q_{bs} = long-wave radiation emitted by the body of water

Q_v = net energy brought into the body of water in inflow, including precipitation, and accounting for outflow

Q_e = energy utilized by evaporation

Q_h = energy conducted from the body of water as sensible heat

Q_w = energy carried away by the evaporated water

Q = increase in energy stored in the body of water

2 Edinger and Geyer (1965) have depicted the heat transfer terms across a water surface as shown on Figure 2, noting temperature dependent terms and typical value. The addition of heated water discharges simply superimposes the heat addition upon the natural dissipations and additions of energy.

3 Figure 3 demonstrates the relationship of rate of heat dissipation to elevation of the water surface temperature over natural temperature and the mechanisms by which this dissipation is achieved. It is significant to note that the rate of heat dissipation for a given rise in temperature is greater in summer than in winter and also that the heat dissipation by evaporation is much greater in summer than in winter.

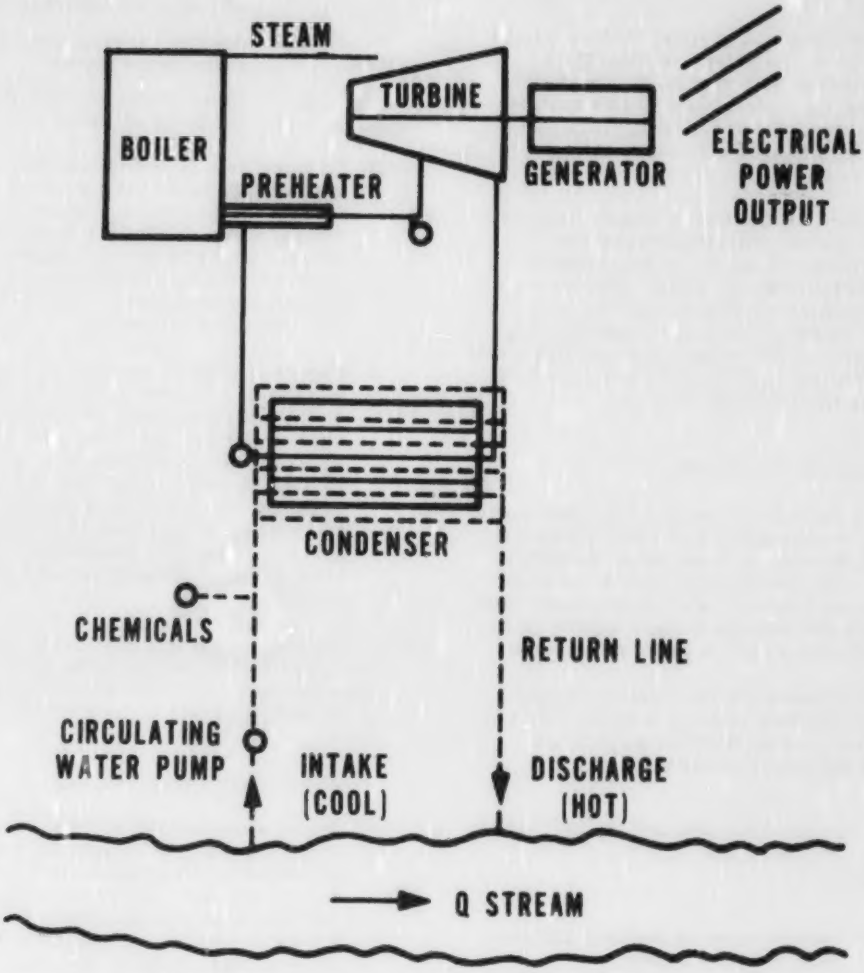
B While the terms in the energy budget are discussed in detail by Anderson (1954) and Edinger and Geyer (1965), brief comments pertaining to their determination are in order.

1 Short wave radiation, Q_s

Short wave radiation originates directly from the sun, although the energy is depleted by absorption by ozone, scattering by dry air, absorption scattering by particulates and absorption and scattering by water vapor. It varies with latitude, time of day, season and cloud cover. Thus, while this quantity can be empirically calculated, it is much better to measure it using a Pyrheliometer which will give the accuracy required for the energy budget.

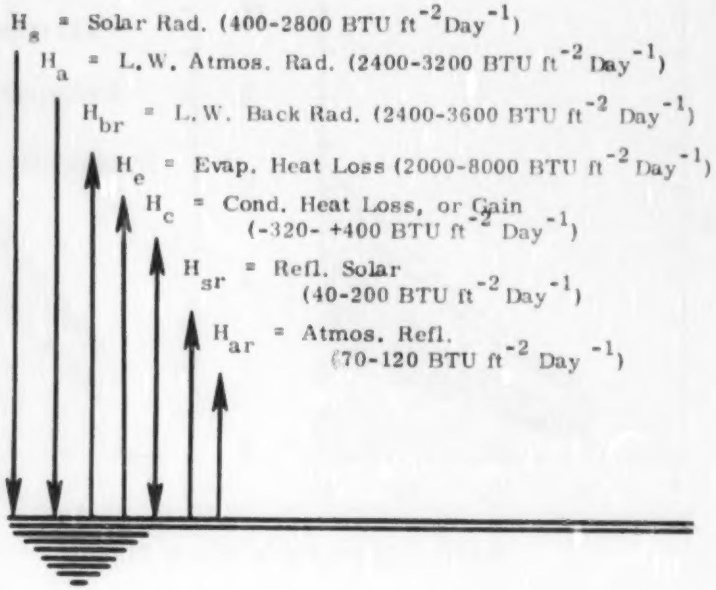
2 Long wave atmospheric radiation, Q_a

Long wave atmospheric radiation depends primarily on air temperature and humidity and increases as the air moisture content increases. It may be a major input on warm cloudy days when direct solar radiation approaches zero. It is



RUN OF THE RIVER ELECTRICITY GENERATING
STATION COOLING SYSTEM

Figure 1


H_s = Solar Rad. (400-2800 BTU ft^{-2} Day^{-1})
H_a = L.W. Atmos. Rad. (2400-3200 BTU ft^{-2} Day^{-1})
H_{br} = L.W. Back Rad. (2400-3600 BTU ft^{-2} Day^{-1})
H_e = Evap. Heat Loss (2000-8000 BTU ft^{-2} Day^{-1})
H_c = Cond. Heat Loss, or Gain (-320- +400 BTU ft^{-2} Day^{-1})
H_{sr} = Refl. Solar (40-200 BTU ft^{-2} Day^{-1})
H_{ar} = Atmos. Refl. (70-120 BTU ft^{-2} Day^{-1})

NET RATE AT WHICH HEAT CROSSES WATER SURFACE

$$\Delta H = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} \pm H_c + H_e) \text{ BTU ft}^{-2} \text{ Day}^{-1}$$

H_R

Absorbed Radiation
Independent of Temperature

Temp. Dependent Terms

$H_{br} \sim (T_s + 460)^4$

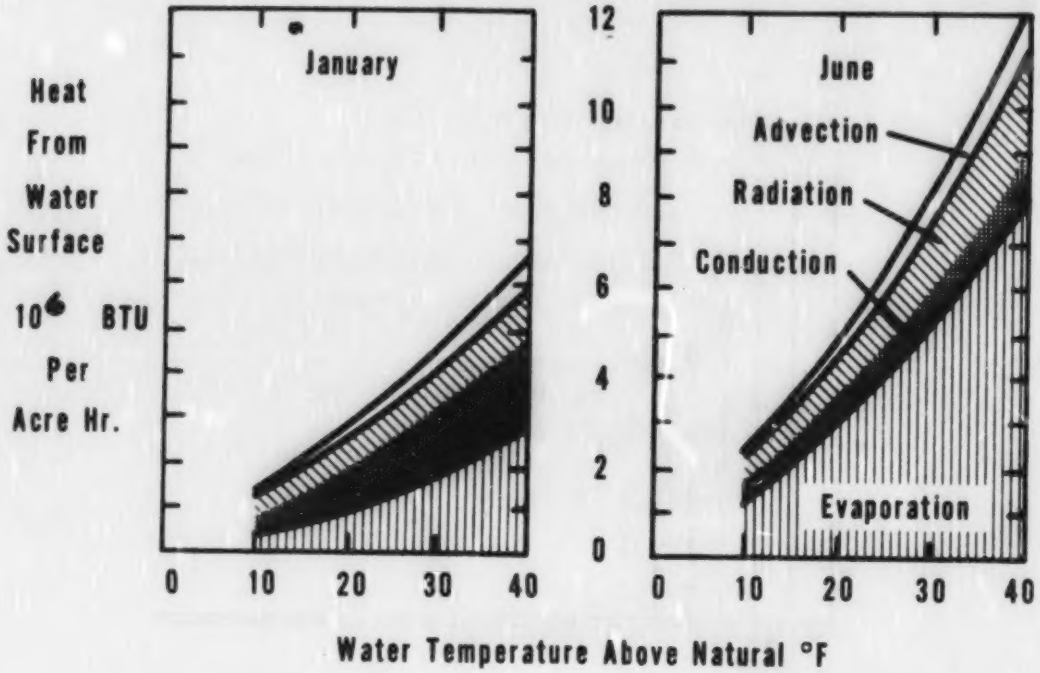
$H_c \sim (T_s - T_a)$

$H_e \sim W (e_s - e_a)$

FIGURE 2

MECHANISMS OF HEAT TRANSFER ACROSS A WATER SURFACE

NOTE: H's are used instead of Q's



HEAT DISSIPATION FROM WATER SURFACE BY EVAPORATION, RADIATION, CONDUCTION, AND ADVECTION DURING JANUARY AND JUNE

Data from Bergstrom (1968) for a water surface in Illinois.

Figure 3

actually a function of many variables, including carbon dioxide and ozone. It can be measured with the Gier-Dunkle Flat Plate Radiometer, although it is more convenient to calculate by empirical formulation than to measure directly.

3 Reflected short wave and long wave radiation, Q_r and Q_{ar}

Solar reflectivity, (R_{sr}), is more variable than atmospheric reflectivity, (R_{ar}), inasmuch as the solar reflectivity is a function of sun altitude and cloud cover, while atmospheric reflectivity is relatively constant. The Lake Hefner studies demonstrated the atmospheric reflectivity to be approximately 0.03, while on an annual basis, the solar reflectivity was 0.06. The Hefner studies used the equation:

$$R_{sr} = a\,S_a^{\,b} \qquad \text{Eq. 2}$$

to determine solar reflectivity, where S_a is the sun altitude in degrees and a and b are constants depending on cloud cover. Note that $R_{sr} = Q_r/Q_s$ and $R_{ar} = Q_{ar}/Q_a$.

4 Long wave or back radiation, Q_{bs}

Water sends energy back to the atmosphere in the form of long wave radiation and radiates almost as a perfect black body. Thus, the Stefan-Boltzman fourth power radiation law can be utilized, or:

$$Q_{bs} = 0.97\sigma\,(T_o + 273)^4 \qquad \text{Eq. 3}$$

where:

0.97 = Emissivity of water

Q_{bs} = long wave radiation in calories/cm^2/day

σ = Stefan-Boltzman constant = 1.171×10^{-7} calories/cm^2/deg^4/day

T_o = water surface temperature in ^{o}Centigrade

All that is required to compute Q_{bs} is the water surface temperature and a table giving the value of Q_{bs} for any temperature, T_o, is readily available or computable.

5 Energy utilized by evaporation, Q_e

Each pound of water evaporated carries its latent heat of vaporization of 1055 BTU's at 68^{o}F, thus Q_e is a significant term in the energy budget. The Lake Hefner study was explicitly promulgated for determining correct evaporation relationships and resulted in the following equation:

$$Q_e = 11.4W(e_s - e_a) = \text{BTU}/\text{ft}^2/\text{day} \qquad \text{Eq. 4}$$

which is of the general type of evaporation formula:

$$E = (a + bW_x)(e_s - e_a) \qquad \text{Eq. 5}$$

where:

a, b = empirical coefficients

W_x = wind speed in mph at some elevation, x ft. above water

e_a = air vapor pressure, mm-Hg

e_s = saturation vapor pressure of water determined from water surface temperature, mm-Hg

E = evaporation = $Q_e/\rho L$ ft/day

ρ = density of evaporated water lbs/ft^3

L = latent heat of vaporization BTU/lb

Many expressions have been developed for estimating the evaporation rate, the coefficients differing because of variation in the reference height for measurement of wind speed and vapor pressure, the time period over which measurements are averaged and local topography and conditions. As stated by Edinger and Geyer (1965), "It would also be expected that the coefficients would be much different for rivers and streams than for lakes and might well be dependent on water velocity and turbulence, particularly in the case of smaller rivers".

6 Energy conducted as sensible heat, Q_h

Heat enters or leaves water by conduction if the air temperature is greater or less than water temperature. The rate of this conductive heat transfer is equal to the product of a heat transfer coefficient and the temperature differential.

A single direct measurement of this quantity is not available and recourse to an indirect method is necessary. The method involves using average figures of air temperature, water surface temperature and humidity for the period in question and computing the ratio of Q_h to Q_e, which is known as the Bowen Ratio and expressed as:

$$R_B = \frac{Q_h}{Q_e} = \frac{0.61\,P\,(T_o - T_a)}{1000\,(e_o - e_a)} \qquad \text{Eq. 6}$$

where:

P = atmospheric pressure in millibars

T_a = temperature of air in ^{o}C

T_o = temperature of water surface in ^{o}C

e_o = saturation vapor pressure corresponding to temperature of water surface in millibars

e_a = vapor pressure of air at height at which T_a is measured in millibars

7 Energy carried away by evaporated water, Q_w

Water being evaporated from the surface is at a higher temperature than the lake water, and thus energy is being removed. This term is relatively small and can be readily computed from the following equation:

$$Q_w = \rho_e\, c\, E\, (T_e - T_b) = \frac{\text{cal}}{\text{cm}^2\text{-day}} \qquad \text{Eq. 7}$$

where:

ρ_e = density of evaporated water, gm/cm^3

c = specific heat of water, cal/gm

E = volume of evaporated water, gm/cm^2/day

T_e = temperature of evaporated water, ^oC

T_b = base or reference temperature, ^oC

8 Advected energy, Q_v

The net energy contained in water entering and leaving the lake may be computed from the following expression:

$$Q_v = c_{si} V_{si} \rho_{si} (T_{si} - T_b) + c_{gi} V_{gi} \rho_{gi} (T_{gi} - T_b)$$
$$- c_{so} V_{so} \rho_{so} (T_{so} - T_b) - c_{go} V_{go} \rho_{go} (T_{go} - T_b)$$
$$+ c_p V_p \rho_p (T_p - T_b) \div A \qquad \text{Eq. 8}$$

in which:

Q_v = advected energy in cal cm^{-2}day^{-1}

c = specific heat of water ($\simeq$ 1 cal g^{-1} deg^{-1})

V = volume of inflowing or outflowing water in cm^3 day^{-1}

ρ = density of water ($\simeq$ 1 cal g^{-1}deg^{-1}

T = temperature of water in ^oC

A = average surface area of reservoir in cm^2

The scripts are as follows:

si = surface inflow

gi = groundwater inflow

so = surface outflow

go = groundwater outflow

p = precipitation

b = base or reference temperature, usually taken as 0^oC

Since some of the terms in equation 8 may not be measurable, a water budget is performed for the same period, evaporation is estimated, and the unknown terms are found by trial and error.

9 Increase in energy stored, Q

The change in storage in the energy-budget equation may be either positive or negative, and is found from properly averaged field measurements of temperature and the following equation:

$$Q = c\rho_1 V_1 (T_1 - T_o) - c\rho_2 V_2 (T_2 - T_o \div At \qquad \text{Eq. 9}$$

in which:

Q = increase in energy stored in the body of water in cal cm^{-2}day^{-1}

c = specific heat of water ($\simeq$ 1 cal g^{-1})

ρ_1 = density of water at T_1 ($\simeq$ 1 g cm^{-3})

V_1 = volume of water in the lake at the beginning of the period of cm^3

T_1 = average temperature of the body of water at the beginning of the period in ^oC

ρ_2 = density of water at T_2 ($\simeq$ 1 g cm^{-3})

V_2 = volume of water in the lake at the end of the period, in cm^3

T_2 = average temperature of the body of water at the end of the period in ^oC

T_o = base temperature in ^oC

A = average surface area in cm^2 during the period

t = length of period in days

III CONCLUSION

From this necessarily brief discussion of the various parameters comprising the energy-balance, it may be concluded that it is possible to predict heat dissipation using these concepts. Obviously, the reliability of the results will depend on the degree of sophistication used in the theoretical approach and the frequency and accuracy of the measurements taken.

ACKNOWLEDGMENT

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This outline was prepared by James A. Montgomery, Sanitary Engineer, Manpower and Training, Pacific Northwest Water Laboratory, Corvallis, Oregon.

THE CONSERVATION OF HEAT IN A BODY OF WATER--
THE ENERGY BUDGET APPROACH TO WATER TEMPERATURE PREDICTION

I INTRODUCTION

A In the past few years, a great deal of work has been done to develop and perfect methods for predicting temperatures in rivers, lakes, reservoirs, estuaries, and marine waters. These methods can be loosely lumped together under the term "mathematical models." Mathematical models can be thought of as groups of equations which together describe a real-world physical phenomena. These equations may or may not be put together in the form of a computer program. Unfortunately, mathematical models are only as good as the assumptions which are used to "build" them. Only on rare occasions is one able to truly simulate a natural process by a mathematical expression and usually reliance is placed on simplifying assumptions to make the equations tractable. The recent developments in the use of high-speed digital computers has led to significant reductions in such simplifying assumptions, but assumptions about real-world processes must still be made in order to be able to construct models to simulate them.

B With these thoughts in mind, let us attempt to build a mathematical model to simulate the temperature regime in a body of water.

The following discussion presents the basic approach which is used to solve temperature prediction problems. However, the mathematical formulation of the physical heat transfer processes which occur is not a simple matter. The scope of this outline prevents a presentation of the mathematical derivations leading to temperature prediction models for all situations. However, a simplified case is presented in the example problem of the next section. For information on more sophisticated models, the reader is urged to consult the technical literature. An excellent basic reference is the Edison Electric Institute's Publication No. 65-902, Heat Exchange in the Environment, by J.E. Edinger and J.C. Geyer, Department of Sanitary Engineering and Water Resources, the Johns Hopkins University, June 1, 1965.

II HEAT TRANSFER MECHANISMS

In order to describe temperature regimes mathematically, it is necessary to consider heat transfer mechanisms in water and between water and the atmosphere. For localized problems, e.g., outfalls or plumes, the mechanisms acting in the water are most important; analysis of conditions throughout larger systems (rivers, reservoirs, etc.) requires emphasis on the air-water heat transfer mechanisms as well as those in water. In either case, specific predictions are desirable so that effective control or management techniques can be applied.

A Heat Conservation

The energy budget approach to water temperature prediction is based upon the idea of conservation of energy, or heat in this case. An equation can be simply written to account for all of the heat entering, leaving, or stored in a body of water.

(Heat In) - (Heat Out) + (Heat Stored) + (Heat Exchange at the Boundaries) = 0

The problem of developing a mathematical model for dealing with any water temperature prediction problem is simply a matter of evaluating these four terms. However, the problems which one must deal with are many times more complex than this statement implies.

1 The first two terms represent the energy entering or leaving a system within masses of water. For example,

in a lake or reservoir, tributary inflow, groundwater inflow, and precipitation represent sources of water, while releases at the dam (or tributary outflows in the case of a lake), and water loss by evaporation represent depletions. In order to assess the effects of these items on the conservation of heat for the system, one needs to know the volume and temperature of the flows. This information is combined with the values for density and specific heat in the following way:

$$\left[(\text{Vol.})(T)(\rho)(C_P)\right] \left[(ft^3)(^{\circ}F)\left[\frac{lb}{ft^3}\right] \frac{BTU}{lb^{\circ}F}\right] = \text{Heat In (or Out) in BTU's}$$

The time rate of change of this heat would be written:

$$\text{Vol. } \rho C_P \frac{dT}{dt}$$

2 The third term involves a determination of the temperature rise or fall within the water body.

Unless the water body is completely mixed (no temperature difference in any of the three physical dimensions at any point in time), it is necessary to describe the distribution of temperature within the water before and after the time period for which the determination of heat storage is to be made (usually rate of heat storage is computed, and thus interest would be in a value in terms of BTU's per unit time). In order to determine the temperature distribution within a body of water, it is necessary to understand the heat transport mechanisms which occur within water. These two mechanisms are called advection and diffusion.

a Advection is the transport of heat energy by the movement of a mass of water. It can occur in all three spacial dimensions of a water body. Longitudinal advection is the downstream movement of heat energy within the river flow. Lateral advection can occur due to a discharge normal to the river flow or because of density gradients. Vertical advection can take place in a stratified system when surface cooling makes a thin upper layer sink promote an upward movement of lower water mass. If the longitudinal, lateral, and vertical axes are designated as x, y, and z, respectively, advection terms are written as:

$$V_x \frac{\partial T}{\partial x}, \quad V_y \frac{\partial T}{\partial y}, \quad V_z \frac{\partial T}{\partial z}$$

b Diffusion of heat energy can occur under both turbulent and laminar flow conditions. Eddy diffusion is a consequence of turbulent flow and results from the movement of small fluid masses called eddies, which are random both in size and orientation. Molecular diffusion occurs under non-turbulent flow conditions and results from the random motion of molecules. Heat transfer by molecular diffusion is much lower than by turbulent diffusion. In most cases molecular diffusion is ignored. Turbulent diffusion is often called turbulent mixing or dispersion, and as with advective heat transfer, it can take place along all three spacial dimensions. Examples of the process of turbulent mixing occurring when a heated effluent is discharged into a flowing stream are shown in Figure 1.

Turbulent mixing can be expressed mathematically as:

$$\frac{\partial}{\partial x}\left[D_x \frac{\partial T}{\partial x}\right], \quad \frac{\partial}{\partial y}\left[D_y \frac{\partial T}{\partial y}\right], \quad \frac{\partial}{\partial z}\left[D_z \frac{\partial T}{\partial z}\right]$$

Where, D_x, D_y, and D_z are coefficients of turbulent mixing (L^2/t).

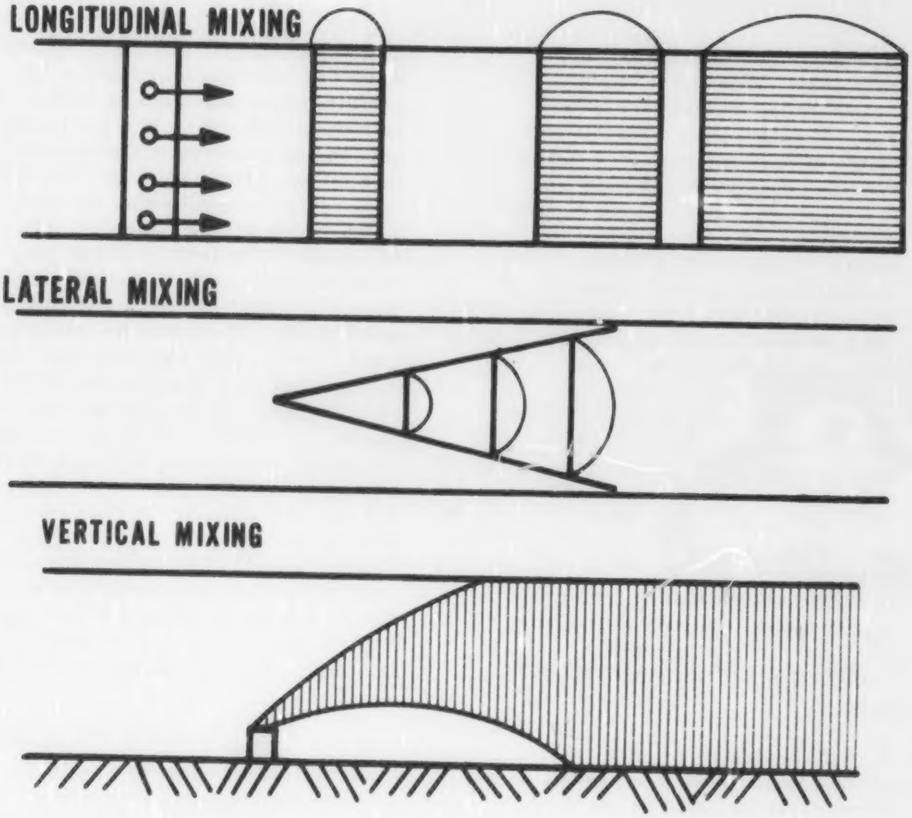
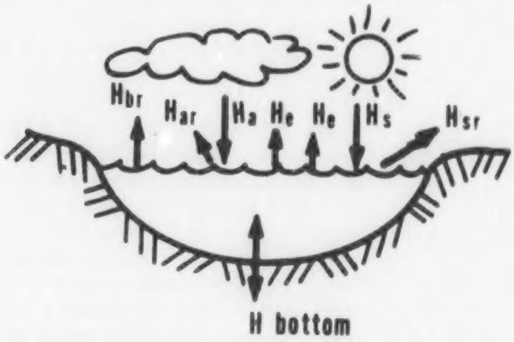


FIGURE 1

3 The fourth term in the heat conservation equation concerns the heat exchange at the boundaries of the water body:



Note: H's are used instead of Q's

As you can see from the sketch, there are eight different mechanisms that can cause heat exchange at the boundaries of the water body. The eighth term, H Bottom, is usually neglected, although under some circumstances it may be significant. It would include terrestrial heating, heat transfer by conduction through the bottom and biological and chemical heating in the bottom sediments.

a Of the seven remaining terms, the magnitudes of four are independent of temperature. These are: H_s, H_a, H_{sr}, and H_{ar}.

1) H_s - Incoming short-wave solar radiation. This is the energy which comes directly from the sun. It falls within a wavelength range of 0.14 microns to 4 microns, reaching maximum intensity at 0.5 microns. The amount of solar radiation reaching a surface normal to the earth's outer atmosphere is almost constant at 10,200 BTU/ft^2 day. Therefore, the amount of solar radiation at any point on the earth's outer atmosphere is a function of latitude, time of day, and season of the year. As the radiant energy passes through the atmosphere, it is diminished by ozone absorption, scattering by gases, absorption, scattering and reflection by particulate matter, and absorption and scattering by water vapor. A normal range of values of incoming solar radiation is 400 to 2800 BTU/ft^2 day.

2) H_a - Incoming long-wave atmospheric radiation. Long-wave radiation is sometimes referred to as "black body" radiation and its magnitude is proportional to the fourth power of the absolute temperature of the radiating body. Within the atmosphere many materials function as radiators of long-wave radiation. They include water vapor, ozone, carbon dioxide, and other gases and particulate matter. Clouds are good radiators of long-wave radiation, and thus one can expect significant increases in atmospheric long-wave radiation on cloudy days. Long-wave radiation falls within a wavelength range of 4 to 120 microns, with a maximum intensity at 10 microns. A normal range of atmospheric long-wave radiation is 2400 to 3200 BTU/ft^2 day.

The physical difference between long-wave and short-wave radiation is exhibited by a phenomenon called "the greenhouse effect." In a greenhouse only the short-wave radiation passes through the glass; however, the black body radiation emitted by the plants, which is long-wave, does not exit from the glass. The bottom of the glass also radiates long-wave radiation and so you have a net heating effect within the greenhouse. In nature the same phenomenon exists. The long and short-wave radiation from the atmosphere impinge upon the ground, the ground then radiates black body radiation, which is long-wave radiation. However, this long-wave radiation cannot penetrate up through the atmosphere and part of it is re-radiated back to the ground, thus having a net heating effect. The reflected short-wave radiation, however, enters back through the atmosphere and is lost into space. This is the reason why on clear nights it's much colder than on cloudy nights.

3) Finally, two surface heat exchange mechanisms which are independent of temperature (as shown on the sketch) are H_{sr} and H_{ar}; both of these are reflected radiation terms. H_{sr} indicates the amount of incoming solar radiation which is reflected by the water surface, and H_{ar} indicates the amount of long-wave radiation which is reflected by the water surface. The reflectivity of incoming short-wave solar radiation is a function of the angle of the sun, the type of cloud cover, the elevation of the clouds, and the amount of cloud cover measured in tenths. At a sun altitude of greater than 40°, the reflected solar radiation is about 5% of incoming short-wave radiation. The reflected atmospheric radiation remains relatively constant at about 3% of the incoming long-wave radiation.

These four terms, H_s, H_a, H_{sr}, and H_{ar}, which are all independent of water surface temperature, can be added together and called "net radiation input" (H_R). Care must be taken to account for their direction during the addition:

$$H_R = H_s + H_a - H_{sr} - H_{ar}$$

b The three terms which are dependent on water surface temperature are:

H_{br}, H_c, and H_e

1) H_{br} is the back radiation emitted from the water surface. It is long-wave radiation and has the same wavelength range as atmospheric long-wave radiation of 4 to 120 microns. Water exhibits the properties of an almost perfect black body so the Stephan-Boltzman fourth power radiational law can be used to compute the amount of black body radiation which is emitted by the water surface. This law states that back radiation from the water surface is proportional to the emissivity of the water, times the Stephan-Boltzman constant, times the absolute water temperature to the fourth power. Normal ranges for long-wave back radiation from the water surface are 2400 to 3600 BTU's/ft^2 day.

2) H_c is the heat exchange due to conduction and convection. This heat exchange is proportional to the wind speed and to the difference between water temperature and air temperature. Normal values for H_c are -300 to +400 BTU's/ft^2 day.

3) Finally, H_e represents the energy lost due to evaporation. For every pound of water which evaporates from the water surface, approximately 1000 BTU's are carried away as latent heat of vaporization. Therefore, if the volume of water evaporated can be computed, it is a very simple matter to compute the amount of energy lost due to evaporation. There are many theoretical and experimental equations for computing evaporation rates; however, the one which is most often used relates evaporation to the product of wind speed and the difference between vapor pressure of saturated air at the water temperature and the water vapor pressure in the overlying air. A normal range for heat loss due to evaporation is 2000 to 8000 BTU's/ft^2 day.

B Thus far, discussion of the energy budget terms has been qualitative. A discussion of the computations and evaluation of each of these terms follows:

The overall heat exchange at the surface of a water body is determined by the algebraic sum of the seven components mentioned above. Such a sum is often referred to as the energy or heat budget of the water surface.

Thus,

$$\text{Net Exchange Rate} = H_s + H_a - H_{ar} - H_{sr} - H_{br} - H_e - H_c$$

Since $H_s + H_a - H_{ar} - H_{sr}$ equals the

Net Radiation Input

The following terms must be evaluated in order to be able to make a water surface energy budget.

1 H_R represents the net atmospheric and solar (long-wave and short-wave) radiation at the water surface. Equations are available which enable the computation of the four components of H_R. Usually, however, one or more of these components are measured directly with appropriate instrumentation.

It is quite common to measure incoming short-wave radiation (H_s) and then compute the other three components.

2 Long-wave atmospheric radiation (H_a) can be computed with any of several empirical formulations. One of the most commonly used is Brunts formula:

$$H_a = 4.5 \times 10^{-8} (T_a + 460)^4 \ (C + 0.031 \sqrt{e_a})$$

where

H_a = Long-wave atmospheric radiation, BTU/ft^2 day

C = An empirical coefficient based on the relationship between air temperature and the ratio of the measured solar radiation to the clear-sky solar radiation.

T_a and e_a should be measured about six feet above the water surface. This equation will provide estimates which are within 10-20% of true values.

3 Preceding comments on the reflected solar radiation (H_{sr}) indicated the factors to be considered in its computation. The empirically developed graphs used in its computation are not presented, but for sun altitudes of less than 40° its evaluation is not extremely reliable.

As stated previously, the long-wave reflected radiation can be assumed to be 3% of the incoming atmospheric long-wave radiation.

4 The information just presented on the computation of the energy budget components of H_R is sketchy. If more information is required, one of the several good references available which cover these equations should be consulted. These references include Edinger and Geyer and a recent publication by TVA, Heat and Mass Transfer Between a Water Surface and the Atmosphere. This excellent reference includes formulations for all components of the energy budget.

The reason the computation of H_R is not stressed is that recent developments in instrumentation now make it possible to measure it directly, and the use of measured values may be preferred over calculated values.

5 Back radiation emitted from the water surface (H_{br}) may be computed by the Stephan - Boltzman radiation law:

$$H_{br} = \gamma_w \alpha (T_s + 460)^4 = (460)^4 \gamma_w \alpha \left(\frac{T_s}{460} + 1 \right)^4$$

$$H_{br} = 1801 \left(\frac{T_s}{460} + .1 \right)^4$$

where γ_w = emissivity of water, 0.97

α = Stephan-Boltzman constant (4.15 × 10^{-8} BTU /ft day°R^4)

T_s = Water Surface Temp, ° F

H_{br} = Back-radiation, BTU/ft^2 day

6 Evaporative heat loss (H_e) is usually computed using an equation of the form:

$$H_e = bw\,(e_s - e_a)$$

where b = Evaporation coefficient

e_s = pressure of saturated water vapor in air at the temperature of the water, mmHg

e_a = pressure of water vapor in ambient air, mmHg

w = wind speed, mph

H_e = Evaporative heat loss, BTU/ft^2 day

The fact that equations of this form are used for computing evaporative heat loss does not mean that it is the best formulation. More realistic equations are available; they require much more sophisticated data for their solution.

The value selected for b is often a point of controversy. The value most often used is the Lake Hefner Coefficient, which for the units shown is 11.4. However, this value was determined empirically at Lake Hefner, and may not be applicable to other localities. Research indicates that when considering streams rather than lakes, a higher value for b is more realistic. Another point to consider is that b is really not a constant. If one looks at the theoretical equations for mass transfer in the turbulent boundary layer it is easy to see that b depends on the stability of the atmosphere. Thus one could use a value for b at a given location that would work fine one time, but which might fail to give the correct answer some other time.

7 H_c, conduction-convection (heat transfer mechanism) is computed by utilizing a relationship between H_c and H_e called the Bowen ratio:

B = Bowen ratio = H_c/H_e

B can be calculated as:

$$B = \frac{0.26\,(T_s - T_a)}{(e_s - e_a)}\ \frac{P}{760}$$

where T_a = air temp, °F

P = atmospheric pressure, mmHg

$$\therefore\ H_c = BH_e = \left[\frac{0.26\,(T_s - T_a)}{(e_s - e_a)} \cdot \frac{P}{760}\right]$$

$$[bw\,(e_s - e_a)]$$

$$H_c \quad 0.26\,bw\,(T_s - T_a) \cdot \frac{P}{760}$$

Usually P/760 is very close to one,

$$\therefore\ Hc = 0.26\,bw\,(T_s - T_a)$$

(A positive Hc indicates a heat loss)

Lumping all these terms together gives:

$$\Delta H = H_R - H_{br} - H_e$$

$$\Delta H = H_R - \overbrace{1801\,\left(\frac{T_s}{460} + 1\right)^4}^{H_{br}} - \overbrace{bw\,(e_s - e_a)}^{H_e} -$$

$$\overbrace{0.26bw\,(T_s - T_a)}^{H_c}$$

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This outline was prepared by James A. Montgomery, Sanitary Engineer, Manpower and Training, Pacific Northwest Water Laboratory, Corvallis, OR.

THE ENERGY BUDGET APPROACH TO WATER TEMPERATURE PREDICTION
EXAMPLE PROBLEM

I INTRODUCTION

This outline presents a problem concerning temperature prediction on a well-mixed stream and the sizing of flow-through cooling ponds. A complete explanation of the methodology is beyond the scope of this outline and the reader is urged to consult the literature for an in-depth review of the many available computational techniques. The problem solution uses basic methods, all of which can be found in the publication by Edinger and Geyer (reference 15 in Bibliography). As an aid in analyzing the problem, references to appropriate pages in this reference are given.

II EXAMPLE PROBLEM AND ITS SOLUTION

A The Situation

A 1000 MW electrical output nuclear power plant of 33% efficiency is to be located on a medium-sized river in the temperate region of the nation. Using applicable hydrologic and meteorologic data, we wish to compute:

1 Downstream temperature, assuming once-through cooling and complete mixing in the river.

2 The area of a flow-through cooling pond necessary to prevent violation of water temperature standards.

B Problem Solution (Part A)

1 Compute the heat energy entering the cooling water.

a For 33% thermal efficiency (n_t):

$$\text{Heat Rate} = \frac{3413}{n_t \div 100} = \frac{3413}{.33} =$$

$$10{,}340 \text{ BTU/KWH}$$

b Assuming a 5% in-plant heat loss:

Heat to cooling water = (0.95 × Heat Rate - 3413) BTU/KWH
Heat to cooling water = [0.95(10,340) - 3413] BTU/KWH
Heat to cooling water = 6410 BTU/KWH
Total heat to cooling water for the 1000 MW (10^6 KW) plant = 10^6 KW × 6410 BTU/KWH = $\underline{6.41 \times 10^9 \text{ BTU/hr}}$

2 Compute the temperature rise in the stream, assuming once through cooling and complete mixing.

Given a design flow in the stream of 3000 cfs, which in terms of lb/hr is:

$$Q = (3500 \text{ cfs})(62.4 \text{ lb/ft}^3)(3600 \text{ sec/hr})$$

$$Q = 7.86 \times 10^8 \text{ lb/hr}$$

Since 1 BTU will raise the temperature of 1 lb of water 1°F,

$$\Delta T_r = \Delta T \text{ in river} =$$

$$\frac{(6.41 \times 10^9 \text{ BTU/hr})}{(7.86 \times 10^8 \text{ lb/hr})(1 \text{ BTU/lb }^\circ\text{F})}$$

$$\Delta T_r = \underline{8.2^\circ\text{F}}$$

3 Equation for computing downstream temperatures

Downstream temperatures are computed by assuming exponential temperature decay. This concept is presented mathematically as:

$$\frac{dH}{dt} = -K(T-E) \quad \text{(Edinger and Geyer, p. 43)}$$

where $\frac{DH}{dt}$ = net rate of water surface heat exchange (BTU ft^{-2} day^{-1})

K = energy exchange coefficient (BTU ft^{-2} day^{-1} $^\circ F^{-1}$)

T = water surface temperature (°F)

E = equilibrium temperature (°F)

For a well-mixed stream, this equation can be written as:

$$\rho C_p y U \frac{\partial T}{\partial x} = -K(T_x - E)$$

(Edinger and Geyer, p. 129)

where ρ = water density (62.4 lb ft^{-3})

C_p = specific heat of water (1 BTU lb^{-1} $^\circ F^{-1}$)

y = mean stream depth (ft)

U = mean stream velocity (ft day^{-1})

$\frac{\partial T}{\partial x}$ = longitudinal temperature gradient ($^oF\ ft^{-1}$)

x = downstream distance (ft)

Define T_o = temperature at x = o; then

$$T_x = (T_o - E)e^{\left[\frac{-Kx}{\rho C_p yU}\right]} + E$$

By defining $\alpha = \frac{-Kx}{\rho C_p yU}$; then

$$\underline{T_x = (T_o - E)e^{\alpha} + E}$$

4 Meteorologic Data

The data shown in Table 1 are used in determining K and E.

5 Determination of K

The energy exchange coefficient is computed using a variation of the equation given on page 48, Heat Exchange in the Environment, by Edinger and Geyer:

$$K = [15.7 + (0.26 + \beta)(bW)]$$

where W = wind speed (mph)

b = experimental evaporation coefficient (a value of 15 is used in this example)

β = proportionality coefficient (see following table)

Range of E (^oF)	β (mm Hg $^oF^{-1}$)
50 to 60	0.405
60 to 70	0.555
70 to 80	0.744
80 to 90	0.990

Thus, for an average daily value of K, using W = 8.5 mph:

$$K = (15.7 + [0.26 + \beta]\ [(15)(8.5)]).$$

Using appropriate values of β for two ranges of E:

E (^oF)	K (BTU ft^{-2} day^{-1} $^oF^{-1}$)
60 to 70	120
70 to 80	144

6 Determination of E

The equilibrium temperature is reached when the rate of change of energy at the water surface equals zero. Edinger and Geyer present a method for computing E. The method involves assuming a likely 10°F temperature range for E and by using the appropriate value for K and the given meteorological data, computing a value for E. If the computed value of E falls within the assumed range, the process is complete. However, if the computed value of E falls outside the assumed range, another range must be

Table 1

	For K	For E			
Time Period (6 hr. intervals)	Wind Speed (W) (mph)	Net Radiation Input (H_R) (BTU ft^{-2} hr^{-1})	Air Temp (T_a) (^oF)	Relative Humidity (%)	Water Vapor Pressure of Ambient Air (e_a) (mm Hg)
Midnight - 6 am	4.0	120	65	40	6.3
6 am - Noon	12.0	290	75	30	6.7
Noon - 6 pm	12.0	320	85	20	6.2
6 pm - Midnight	6.0	130	70	35	6.6
DAILY AVERAGE	8.5	215	74	--	6.5

assumed and the process repeated until E falls within the proper limits. Thus, E is computed by a trial and error method.

For the stated meteorological conditions and computed values of K, we can determine a daily average E by the following seven steps:

Step 1. Assumed range of E = 70 to 80°F

Step 2. Compute F(K) for use in Step 6:

$$F(K) = \frac{K - 15.7}{K}$$

As computed for an E range of 70 to 80°F, $K = 144 \text{ BTU ft}^{-2} \text{ day}^{-1}\ {}^{\circ}\text{F}^{-1}$

$$\therefore F(K) = \frac{144 - 15.7}{144} = 0.891$$

Step 3. Compute E_1 for use in Step 6.

$$E_1 = \frac{H_R - 1801}{K}$$

From the meteorologic data table, $H_R = 215 \text{ BTU ft}^{-2}\text{hr}^{-1}$ or in terms of days, $H_R = 5160 \text{ BTU ft}^{-2} \text{ day}^{-1}$

$$\therefore E_1 = \frac{5160 - 1801}{144} = 23.3$$

Step 4. Compute E_2 for use in Step 6:

$$E_2 = \frac{(0.26)\ (T_a)}{(0.26 + \beta)}$$

From the meteorologic data table, $T_a = 74°F$, and from the table of E range vs. β, $\beta = 0.744$

$$\therefore E_2 = \frac{(0.26)(74)}{(0.26 + 0.744)} = 19.2$$

Step 5. Compute E_3 for use in Step 6:

$$E_3 = \frac{e_a - C(\beta)}{(0.26 + \beta)}$$

From the meteorologic data table, $e_a = 6.5$ mm Hg. $C(\beta)$ is related to ranges of E as follows:

Range of E (°F)	C(β) (mm Hg)
50 to 60	-11.22
60 to 70	-20.15
70 to 80	-33.30
80 to 90	-53.33

Thus for an E range of 70 to 80°F, $C(\beta) = -33.3$

$$\therefore E_3 = \frac{6.5 - (-33.3)}{(0.26 + 0.744)} = 39.6$$

Step 6. Compute M for use in Step 7:

$$\therefore M = E_1 + F(K)\ (E_2 + E_3)$$

$$M = 23.3 + (0.891)\ (19.2 + 39.6) = 75.7$$

Step 7. Compute E using the following relationship:

$$M = E + \frac{0.051E^2}{K}$$

Inserting M and K and setting up a quadratic equation gives:

$$E^2 \left(\frac{0.051}{144}\right) + E - 75.7 = 0$$

$$\therefore 0.000354E^2 + E - 75.7 = 0$$

Solving this equation using the quadratic formula gives:

$$E = \frac{-1 \pm [1 - (4)\ (0.000354)(-75.7)]^{1/2}}{2\ (0.000354)}$$

$$E = \frac{-1 \pm (1.10719)^{1/2}}{0.000708} = \frac{-1 \pm (1.05223)}{0.000708}$$

Rejecting the negative value gives:

$$E = \frac{0.05223}{0.000708} = \underline{73.8°F}$$

(This value is acceptable because it falls within the assumed range of 70 80°F.)

7 Compute average stream velocity

$Q = 3500$ cfs

Given an average cross section 800 feet wide and 5 feet deep:

$$U = \frac{3500 \text{ ft}^3 \text{ sec}^{-1}}{(800 \text{ ft})(5 \text{ ft})} = 0.875 \text{ ft/sec} = \underline{75,600 \text{ ft/day}}$$

8 Evaluation of α

$$\alpha = \frac{-Kx}{\rho C_p y U}$$

For x' in miles: $\alpha = \dfrac{-(144)\ (5280)x'}{(62.4)(1)(5)(75,600)}$

$$\alpha = \underline{-0.0322x'}$$

9 Solve for $T_{x'}$ for $x' = 10, 20, \ldots . 50$ miles

Assume unheated river temperature = 74°F

$$\therefore\ T_o = 74^\circ F + \Delta T_R = 74^\circ F + 8.2^\circ F = 82.2^\circ F$$

$$T_{x'} = (T_o - E)e^{-0.0322x'} + E$$

For x' = 10 miles

$$T_{x'} = (82.2 - 73.8)e^{-(0.0322)(10)} + 73.8$$

$$T_{x'} = (8.4)e^{-0.322} + 73.8$$

$$T_{x'} = (8.4)(0.725) + 73.8 = 79.9^\circ F$$

For x' = 20 miles

Use same value of α and replace T_o by $T_{x'}$ for x' = 10 miles:

$$T_{x'} = (79.9 - 73.8)(0.725) + 73.8 = \underline{78.2^\circ F}$$

For x' = 30, 40, 50 miles

Following the same procedure:

30 miles, $T_{x'} = (78.2 - 73.8)(0.725) + 73.8 = 77.0^\circ F$

40 miles, $T_{x'} = 76.1^\circ F$

50 miles, $T_{x'} = 75.5^\circ F$

These values represent the exponential temperature decay which is graphically shown on the following plot:

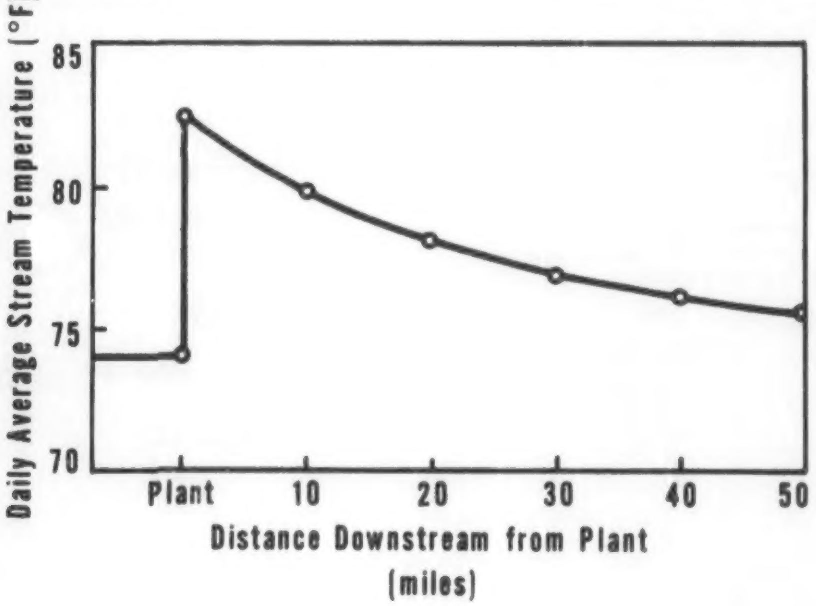
10 This graph presents an idealized picture of the downstream temperatures, since the computations were based on average daily conditions, and thus no diurnal effect is evident. It also assumes that the weather data on which K and E are based are indicative of conditions along the 50-mile stretch of the river. In addition, no tributary inflows or heated discharges are accounted for in the 50 miles.

11 The diurnal effect may be evaluated by using the six-hour average meteorologic conditions given previously. Following the methods described, values of K and E were computed as:

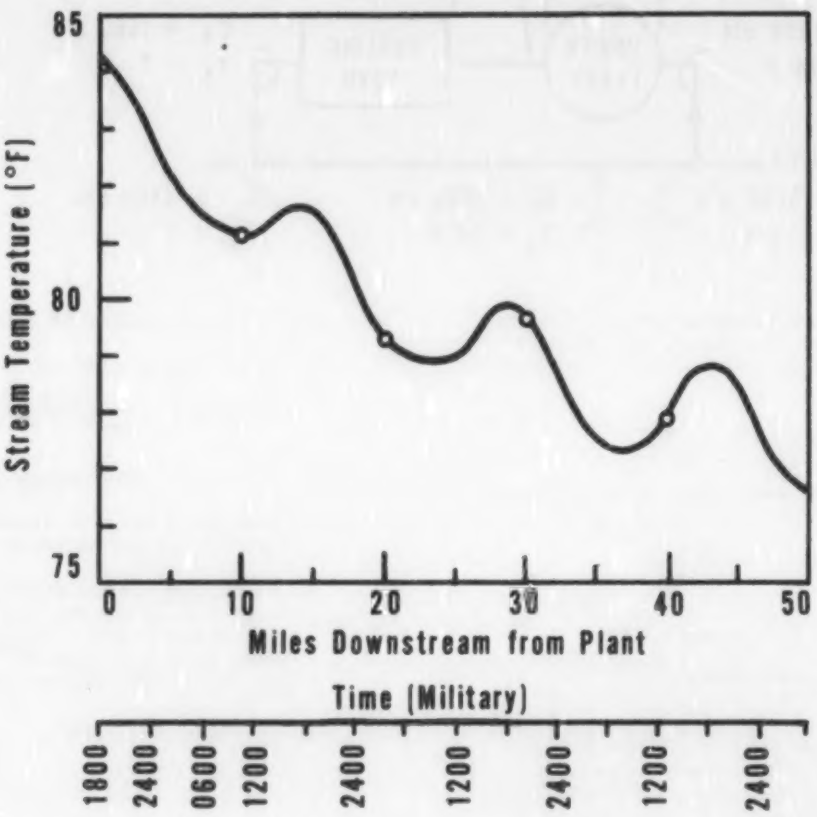
Time Period (6 hr. intervals)	K (BTU $ft^{-2}day^{-1}$)	E (°F)	T_o (°F)
Midnight to 6 am	56	53.8	71
6am to Noon	196	79.2	72
Noon to 6 pm	241	84.0	78
6 pm to Midnight	76	58.1	76

The values of water temperature (T_o) just upstream from the plant reflect natural diurnal fluctuations.

12 Using the exponential temperature decay relationship presented previously and assuming slug flow in the stream, i.e., no longitudinal mixing, the variation in temperature was computed for a parcel of water which left the plant location at 6 pm. The following graph demonstrates the effect of diurnal variations in meteorological conditions of the temperature of the water parcel for a distance of 50 miles downstream.



TEMPERATURE OF A WATER PARCEL



Note that the initial temperature of the parcel is equal to the natural stream temperature (T_O) plus the temperature increase of 8.2°F caused by the plant discharge.

C Problem Solution (Part B)

1 Assuming a maximum allowable daily average stream temperature of 80°F, what flow-through cooling pond area would be required at the site? The sketch on the following page describes the plant-river-pond layout.

2 Temperature rise through plant

Heat to cooling water = 6.41×10^9 BTU/hr

Condenser flow = 1500 cfs - 3.37×10^8 lb/hr

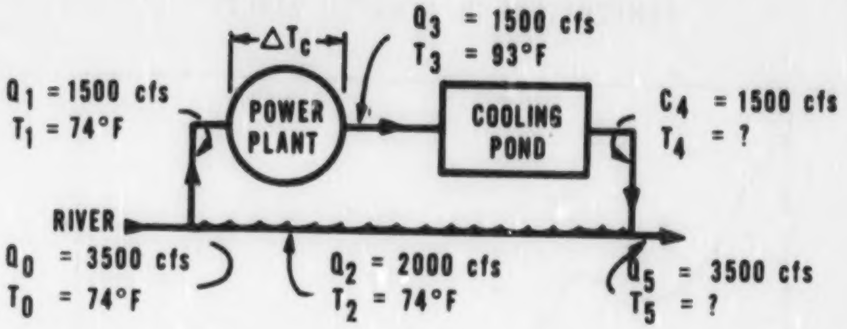
ΔT_c = ΔT through condenser =

$$\frac{(6.41 \times 10^9 \text{ BTU hr}}{(3.37 \times 10^8 \text{ lb/hr})(1 \text{ BTU lb}^\circ\text{F}} = 19.0^\circ\text{F}$$

$$\therefore \quad T_3 = 74^\circ\text{F} + 19^\circ\text{F} = \underline{93^\circ\text{F}}$$

3 Temperature drop through pond

A flow-through cooling pond is assumed to be well mixed in each cross section, but as in a stream, there is a longitudinal temperature decay. Thus, the equation for predicting the temperature drop through the pond is equivalent to the exponential temperature decay equation used on well-mixed streams.



a Using the temperature subscripts given on the sketch, the temperature from the pond can be computed by:

$$T_4 = (T_3 - E)e^{-\alpha'} + E$$

Edinger and Geyer, Heat Exchange in the Environment, p. 113.

where $\alpha' = \dfrac{KA}{\rho C_p Q_3}$

Q_3 = plant discharge (ft^3 day^{-1})
A = pond area (ft^2)

b Using an experimental evaporation coefficient (b) of 12, $K = 118$ and $E = 76.9^oF$. These values are used in the subsequent cooling pond calculations.

Case I - Pond area required for discharge from pond = 80^oF.

$\therefore\ T_4 = 80^oF$

Solving the prediction equation for α':

$80 = (93 - 76.9)e^{-\alpha'} + 76.9$

$e^{-\alpha'} = (80 - 76.9)/(93 - 76.9)$

$e^{-\alpha'} = 0.193$

$\therefore\ \alpha' = 1.65$

Solving the α' equation for A:

$$\alpha' = \frac{118A}{(62.2)(1)(1500)(24\ hr/day)(3600\ sec/hr)}$$

$\alpha' = (1.46 \times 10^{-8})A = 1.65$

$\therefore\ A = (1.65)/(1.46 \times 10^{-8}) =$

$11.3 \times 10^7\ ft^2$

In acres: $A = \dfrac{(11.3 \times 10^7 ft^2)}{(4.36 \times 10^4 ft^2/acre)} =$

$\underline{\text{2590 acres}}$

Case II - Pond area required for mixed river temperature = 80^oF.

If a mixing zone is allowed in the stream such that the mixed river temperature below this zone is equal to or less than 80^oF, a much smaller pond could be used.

Referring to the sketch:

$$T_5 = \frac{T_4Q_4 + T_2Q_2}{Q_5} = 80^oF$$

Solving for T_4:

$$T_4 = \frac{T_5Q_5 - T_2Q_2}{Q_4} = \frac{(80)(3500)-(74)(2000)}{1500}$$

$\therefore\ T_4 = 88.0^oF$

By using the same computational techniques as for Case I:

$\alpha' = 0.373$

$\therefore\ A = (0.373)/(1.46 \times 10^{-8}) =$

$2.55 \times 10^7\ ft^2$

In acres: $A = \dfrac{(2.55 \times 10^7\ ft^2)}{(4.36 \times 10^4 ft^2/acre)} = \underline{\text{585 acres}}$

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This outline was prepared by James A. Montgomery, Sanitary Engineer, Manpower and Training, Pacific Northwest Water Laboratory, Corvallis, Oregon.

PREDICTION OF WATER TEMPERATURES IN RIVERS AND STREAMS- THE EXPONENTIAL DECAY OF TRANSIENT TEMPERATURES

I INTRODUCTION

The computational methodology for the prediction of stream temperature in rivers differs somewhat from that used for reservoirs because of the difference in their physical characteristics. Because of the dynamic nature of a river, relatively short periods must be used to account for diurnal fluctuations in meteorological phenomenon. Allowance must also be made for stream velocity and changes in hydraulic geometry. There are two currently used methods for predicting stream temperatures. One method uses a combination of an energy budget or other method to determine the steady-state, equilibrium, temperature of the stream, and the subsequent imposition of the transient temperature, which is assumed to decay downstream in an exponential manner.

II EXPONENTIAL DECAY OF TRANSIENT TEMPERATURES

A LeBosquet (1946) proposed a mathematical basis for predicting heat loss in a flowing stream using river flow, temperature differential between water and air, hydraulic characteristics and a heat loss coefficient. While the method appears to be quite useful, it is somewhat limited because the value of the heat loss coefficient must be obtained from field observations. LeBosquet found the coefficient to vary from 6 to 10 BTU/ft^2/hr/°F of excess water temperature over air.

The mathematical model proposed is:

$$\frac{dF}{dt} = -\frac{KA_sF}{L} \qquad \text{Eq-1}$$

where:

K = Heat loss coefficient, BTU/ft^2/hr/°F of excess temperature of water over air

F = Excess temperature of water over air at distance, D miles, °F

A_s = Surface area, ft^2

L = Weight of water, lbs

Integration and simplification of this equation yields:

$$K = \frac{Q \log_{10} \frac{F_A}{F}}{0.0102\ WD} \qquad \text{Eq-2}$$

where:

Q = Average discharge, cfs

F_A = Initial excess temperature, °F (water over air)

W = Average stream width, ft

D = Reach distance, miles

It should be noted that the driving force utilized by LeBosquet is incorrect, inasmuch as the water will tend to approach some equilibrium water temperature rather than the temperature of the air.

B Gameson et al., (1960-61) made an exhaustive study on heated discharges into the Thames Estuary and proposed the following mathematical model describing the process:

$$\frac{d\theta}{dt} = -\frac{f}{z}\theta \qquad \text{Eq-3}$$

where:

θ = Initial temperature increment

f = Exchange coefficient

z = Average river depth

t = Time

Using statistical methods, they defined the natural or equilibrium temperature, T_E, as:

$$T_E = 0.5 + 1.109\ Ta \qquad \text{Eq-4}$$

where:

Ta = Air temperature, °C

The solution to this equation utilized was:

$$\theta_t = \theta_0 \exp - \int_0^t \frac{f}{z}\, dt \qquad \text{Eq-5}$$

where:

θ_0 = Initial excess temperature

θ_t = Excess temperature after a time length equal to two tides

Values of the exchange coefficient for the Thames Estuary were found to average approximately 4 cm/hr.

C Velz and Gannon (1960) assumed that the rate of temperature change is directly proportional to the rate of heat loss from the water surface,

$$\frac{dT_w}{dt} = - \frac{H}{62.4b} \qquad \text{Eq-6}$$

Their solution was:

$$A = -224,640 \int_{T_1}^{T_2} \frac{dT_w}{\alpha\,(V_w - V_e) + \beta\,(T_w - E)} \qquad \text{Eq-7}$$

where:

A = Surface area of the river between the points where $T_w = T_1$ and $T_w = T_2$, ft^2/cfs stream flow

V_w = Saturation vapor pressure corresponding to surface temperature T_w, in Hg

V_E = Saturation vapor pressure corresponding to surface temperature E, in Hg

E = Equilibrium temperature, °F (unknown)

α = $0.00722\ H_v\ C\ (1. + 0.1\ W)$

T_w = Water temperature, °F

t = Time, hr

H = Rate of heat loss from the water surface, BTU ft^{-2} hr^{-1}

b = Depth of the river, ft

62.4 = Product of the water density and heat capacity; BTU ft^{-3} °F^{-1}

β = $(1.8 + 0.16\ W)$

H_v = Latent heat of vaporization, BTU lb^{-1}; at assumed water temperature

C = Evaporation coefficient ranging from 10-15

W = Windspeed at 25 feet above water surface, mph

T_a = Air temperature, °F

V_a = Vapor pressure of the air, in. Hg

H_s = Heat gain by solar radiation; BTU ft^{-2} hr^{-1} (measured)

They derived a relationship for the long-term unheated equilibrium water temperature as follows:

$$(1.8 + 0.16W)\ E + 0.00722\ H_v C\ (1 + 0.1W)\ V_E = (1.8 + 0.16W)\ T + 0.00722\ H_v C\ (1 + 0.1W)\ V_a + H_s \qquad \text{Eq-8}$$

This equation is solved by successive approximation, assuming values for the equilibrium temperature and using Meyer's evaporation formula. The resulting value of E, the equilibrium water temperature is then used in the following working equation to estimate the required water surface area for cooling:

$$A = -224,640 \sum_{T_1}^{T_2} \frac{\Delta T_W}{\alpha(V_W - V_E) + \beta(T_W - E)} \qquad \text{Eq-9}$$

The total increment of temperature between the initial heated condition and the desired downstream temperature is divided into equal increments (ΔT_W) with T_W and V_W the mean temperature and mean saturation vapor pressure in each increment. Long-term weather averages are used in the computations.

D Duttweiler (1963) proposed a mathematical model for stream temperature by equating the heat gained in an incremental reach of stream to the time change in enthalpy of the water in the reach. As in previous studies, Duttweiler assumed that the time rate of temperature increase is proportional to the deficit between the actual temperature and some equilibrium temperature. The resulting one dimensional model was:

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} = \frac{1}{\rho c}\,\frac{\lambda}{z}\,(T_E - T) \qquad \text{Eq-10}$$

where:

T = Water temperature

t = Time

v = Velocity at x and t

x = Distance along the stream

ρ = Water density

c = Heat capacity of water

λ = Parameter dependent upon atmospheric conditions

z = Hydraulic depth of the stream or the cross-sectional area divided by the surface width

T_E = Equilibrium water temperature

Using Lagrangian coordinates, the expression for river temperature becomes:

$$\frac{dT}{dt} = \frac{1}{\rho c}\,\frac{\lambda}{z}\,(T_E - T) \qquad \text{Eq-11}$$

and its position may be found from:

$$X - X_o = \int_{t_o}^{t} v\,dt \qquad \text{Eq-12}$$

It is obvious that $\lambda\,(T_E - T)$ is the net heat transfer rate through the air-water interface, $\frac{dH}{dt}$, if evaporation losses, Q_W, are excluded, or:

$$\lambda\,(T_E - T) = \frac{dH}{dt} + Q_W \qquad \text{Eq-13}$$

Duttweiler presents values for λ based on published meteorological data and gives solutions to equations 10 and 12 in integral form.

E Edinger and Geyer (1965) proposed that the net rate of heat transfer through the air water interface was represented by:

$$\frac{dH}{dt} = -K(T - E) \qquad \text{Eq-14}$$

where:

ΔH = Net heat transfer rate through air-water interface, BTU/ft^2/day

E = Equilibrium temperature, °F

T_x = Water surface temperature, °F

K = Exchange coefficient, BTU/ft^2/day/°F

Nomograms for determining E when K is known were presented and methodology defining the exchange coefficient were given.

Assuming that the river reach considered was at steady state, they proposed one-dimensional and two-dimensional models for temperature prediction. The one dimensional model was:

$$\rho C_p yU \frac{\partial T}{\partial x} = -K(T_x - E) \qquad \text{Eq-15}$$

and the two-dimensional model, which accounts for lateral mixing and advection was:

$$U \frac{\partial T}{\partial x} + D_2 \frac{\partial^2 T}{\partial x_1^2} + \frac{K}{\rho C_p d}(T - E) = 0 \qquad \text{Eq-16}$$

The solution presented for equation Eq-15 was:

$$\frac{T_x - E}{T_m - E} = \exp\left[-\frac{Kx}{\rho C_p yU}\right] \qquad \text{Eq-17}$$

and for equation Eq-16:

$$\frac{T_x - E}{T_o - E} = \exp\left[-\frac{C_2 + \alpha^2}{C} x_1\right] \exp[-\alpha x_1] \cdot \frac{\exp[-2\alpha(W - x_1)]}{1 + \exp[-2\alpha W]} \qquad \text{Eq-18}$$

where:

ρ = Water density, lb/ft^3

C_p = Heat capacity of the water, BTU/lb

U = Mean velocity of the stream at x_1, ft/day

y = Mean depth of the stream at x , ft

$\frac{\partial T}{\partial x}$ = Longitudinal temperature gradient, °F/ft

T = Water temperature, °F

x = Longitudinal distance on the stream, ft

D_2 = Lateral mixing coefficient, assumed constant over the channel, ft^2 day^{-1}

x_2 = Distance across the stream, ft

T_o = Temperature of a thermal discharge at the point $x_1 = x_1 = 0$, °F

$C_1 = U/D_2$, ft^{-1}

$C_2 = \frac{K}{C_p dD_2}$, ft^{-2}

α = Coefficient depending on boundary conditions

W = Stream width, ft

T_m = Water temperature at upstream end of reach, °F

Edinger and Geyer's study includes basic concepts of the energy balance.

Several useful models of temperature distribution in reservoirs and rivers are presented and ensuing applications of the methods presented demonstrate the methodology. However, the difficulties encountered in applying the nomograms are not sufficiently stressed. Also, the systems studied are primarily steady-state in nature or the temperatures are known and the transfer coefficients are computed rather than the usual case of attempting to predict the temperatures.

F The work of the advanced seminar at Johns Hopkins University should also be mentioned (Anon. 1962), where the following conclusions were drawn:

1 The quantitative determination of heat transfer within a natural body of water, or between a body of water and its surroundings, is extremely difficult and complex.

2 Temperature change within a body of water is primarily effected by the operation, either independently or jointly, of two mechanisms: turbulent mixing of two or more batches of water of different temperatures eventually resulting in a single batch of water at the weighted mean temperature; and

heat exchange of the water with its surroundings, primarily the atmosphere, governed by the mechanisms of conduction, convection, evaporation, condensation, and radiation.

3 Temperature change is effected to only a minor degree by molecular diffusion and conduction within the body of water.

4 Forecasting of heat loss from artificially heated batches of water may be attempted by use of certain of three principal techniques depending on the availability of data and on the adherence of the specific situation to certain specialized requirements.

5 Where heat is discharged to a stream from a point source, and where complete vertical mixing may be assumed, turbulent mixing may be considered the dominant heat transfer mechanism until horizontal mixing is complete; that is, until that downstream transect is reached where the cross-section temperature is uniform from bank to bank.

6 Assuming that there is no horizontal temperature gradient, either as a result of effective turbulent mixing as described in No. 5 above, or as a result of heat discharge from a thoroughly diffused source, and assuming complete vertical mixing, heat loss may be evaluated by either use of the heat budget theory method or equilibrium temperature theory method.

7 The complexity of the heat budget theory makes this method infeasible for field use except where extremely precise, reliable, and rugged instrumentation is available.

8 At present, not all of the instrumentation required by No. 7 above is available.

9 The relative simplicity of the equilibrium theory method, coupled with its feasibility for use under field conditions suggests its use for forecasting heat loss both in specific field situations and in generalized design situations using combinations of ambient conditions selected according to statistical considerations.

IV SUMMARY

A The excellent summary prepared by Roesner (1969) compares several of the previously described models:

"Although the models discussed in this section appear quite different in the form of their solutions, some of them are actually quite similar and could be expected to produce nearly the same answers when applied to a given problem. For example, it can be shown that Schroepfer's model and the Advanced Seminar model differ only in the following respects:

1 Method of computing long-wave atmospheric radiation

2 Units and empirical coefficients used

3 Inclusion of heat exchange by eddy diffusion by the Advanced Seminar

B By comparing differential forms, it can be shown that the models of Gameson, Gibbs, and Barrett, Velz and Gannon, Duttweiler, and Edinger and Geyer are very similar. For ease of comparison, the models are collected in Table 1. Consider a river reach which is receiving a thermal discharge and observe the following (assuming consistent units):

1 If mean daily or monthly temperatures are used for the natural stream temperature, the equilibrium temperature of Duttweiler (T_E) and of Edinger and Geyer (E) can be considered equal to the natural river temperature. Thus ($T - T_E$) and (T - E) can be equated to Gameson, Gibbs, and Barrett's excess temperature θ, i.e.

$$\theta = (T - T_E) = (T - E)$$

TABLE 1

COMPARISON OF STREAM TEMPERATURE PREDICTION MODELS

Gameson, Gibbs, and Barrett

$$\frac{d\theta}{dt} = -\frac{f}{z}\theta$$

where θ = excess of water temperature over natural water temperature

f = exchange coefficient

z = mean river depth

Velz and Gannon

$$\frac{dT_w}{dt} = \frac{H}{62.4b}$$

where T_w = water temperature

H = rate of heat loss from water surface

b = river depth

Duttweiler

$$\frac{dT}{dt} = \frac{1}{\rho c}\frac{\lambda}{z}(T_E - T)$$

where T = water temperature

λ = parameter dependent on atmospheric conditions

z = hydraulic depth

T_E = equilibrium temperature

Edinger and Geyer

$$C_\rho U d \frac{\partial T}{\partial x_1} = -K(T - E)$$

where T = water temperature

U = mean stream velocity

d = mean stream depth

K = exchange coefficient

E = equilibrium temperature

ρ = water density

2 The time of travel t, and the longitudinal distance along the stream x, are related as

$$\frac{dx}{dt} = U$$

where U is the mean velocity of the stream at the point x; thus

$$\frac{dT}{dt} = U \frac{dT}{dx}$$

3 If the time base for travel time is short compared to the time interval for which the natural stream temperature is averaged, then E and T_E can be considered constant and

$$\frac{d\theta}{dt} = \frac{d(T - T_E)}{dt} = \frac{dT}{dt}$$

and

$$\frac{d\theta}{dt} = \frac{d(T - E)}{dt} = \frac{dT}{dt} = U \frac{dT}{dx}$$

4 By use of items (1) and (3), it is observed that

$$f = \frac{\lambda}{\rho C} = \frac{K}{\rho C}$$

The essential difference is that λ and K are defined in terms of atmospheric variables and parameters, while f is strictly empirical.

5 It is observed that the net rate of heat loss from the river H, in Velz and Gannon's model can be equated as

$$H = \lambda\ (T - T_E) = K\ (T - E)$$

Thus for the conditions stated in item (1) the basic models of Gameson, Gibbs, and Barrett; Duttweiler; Edinger and Geyer; and Velz and Gannon can be considered identical. The solutions however will not give identical answers because of the different approaches taken in integrating the individual models. The other models reviewed here are individualistic either in their derivation or in the methods used to obtain the working equation and thus cannot be compared.

C The models described above define the state of development of temperature prediction equation for streams. Note that all the models presented here are one-dimensional except for Edinger and Geyer's two-dimensional model which is quite simplified."

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WATER TEMPERATURE AND PREDICTION

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THERMAL POLLUTION CONTROL METHODS

I INTRODUCTION

Nationally, thermal pollution has become an increasingly important topic for consideration in water management and pollution control circles. With the approval of State-Federal water quality standards, the criteria and implementation plans for control of waste heat discharges have been established. This outline will consider several of the accepted methods now being used to control thermal pollution.

II CONTROL IN INDUSTRY

A Industrial process changes to reduce waste heat production.

Efficiency gains in fossil-fueled, steam-electric stations have reduced their waste heat discharge rate by approximately one-half over the past 30 years. Such gains have been accomplished through a number of refinements in the plant itself and in operating conditions, which increases the overall plant thermal efficiency by reducing the amount of heat entrained in the exhaust steam. The refinements that have been developed include the following:

1 Increasing steam pressure--elevating the steam pressure at the turbine entrance reduces exhaust heat by varying increments, but in general a 100 psi pressure increase will reduce exhaust heat per unit of electricity by 0.4%.

2 Superheating steam--steam generated in the boiler is heated even more in a superheat section of the furnace. Each 50°F additional temperature rise reduces exhaust heat per unit of electricity by about 1.4%.

3 Reheating steam--after the steam has passed through the high-pressure turbine section it is returned to the furnace reheat section to absorb additional heat energy. Again, each 50°F increase here reduces exhaust heat per unit of electricity by about 1.4%.

4 Boiler feedwater heating--a portion of the steam is withdrawn before it reaches the final turbine exhaust, thereby eliminating its passage through the condenser. This steam is utilized to increase the temperature of water entering the boiler. Feedwater heating can reduce exhaust heat up to 37% per unit of electricity, depending on the number of heaters used.

5 Reducing exhaust pressure--the pressure in the condenser is transmitted to the turbine exhaust, i.e., turbine backpressure. This pressure influences heat rejection to the extent that each 1 psi reduction in pressure reduces exhaust heat per unit of electricity by 2.5%.

Modern power plants are designed to make use of these efficiency refinements as much as possible. Through such techniques, new fossil-fueled plants attain efficiencies near 40%; nuclear-fueled plants about 33%.

B Development of new methods of power generation producing less waste heat production.

Generating processes are more efficient today than they were 25 to 30 years ago, but they are still not good enough. Today, we use about 10,000 BTU's to produce one kwhr, on the average, compared with 16,500 BTU's per kwhr in 1938. Some highly efficient new plants are down to 8,900 BTU's per kwhr, but this is still only 38.2% efficiency. The Federal Power Commission suggests that average heat rates of 8,500 BTU's per kwhr are likely by 1980. While this would reduce thermal pollution by almost 20%, it still means only 40.2% efficiency. At best,

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then, by 1980, 60% of the heat from a coal-fired plant will be wasted and will have to be put to other uses or dissipated.

New and non-polluting methods of power generation are being intensively researched. High temperature gas turbine-blade cooling could result in a 50% reduction of the cooling waters required. Electrogasdynamics, magnetohydrodynamics, and thermionic power generation, if they can be developed economically, could greatly reduce our water- and air-pollution problems. Fuel cells and thermal electrical systems which do not require steam cycles for power generation also are being studied and present hope for the future.

1. Gas turbines--air is taken from the atmosphere, compressed, and subsequently burned with a liquid or gaseous fuel. The resulting high-temperature, high-pressure gases expand through a power turbine and then exit to the atmosphere.

   Today's gas turbine efficiencies of less than 25% are not competitive for power production on a large scale, although some relatively small turbines are being used for standby and peaking operation. Future development may achieve higher operating temperatures and increased air flow, which in turn would increase efficiency to a level near that of fossil-fueled steam plants.

   Heat exhausted from gas turbines might possibly be put to use in a conventional steam-electric plant. Such a combination would reduce the waste heat discharge rate, although cooling water would still be used.

2. Fuel cells--fuel cells are somewhat similar to conventional storage batteries in that they consist of two electrodes separated by an electrolyte. The fuel cell does not contain a store of energy; it generates current as long as fuel and oxidant supply chemical energy for conversion to electricity.

   Individual fuel cells produce very small quantities of power. Hence, thousands of cells would have to be connected in groups to increase power output to a level which would permit large-scale production. Predicted eventual efficiencies of 50 to 85% is a further attribute of the fuel cell system.

3. Magnetohydrodynamics (MHD) generators--MHD generators utilize the principle of passing a conductor through a magnetic field to produce current. In this system the moving conductor is an ionized gas. Very high temperatures and gas velocities must be maintained, which at the present time presents some major technical difficulties. In theory, the application of a MHD generator can be visualized, possibly in combined operation with a conventional steam plant, but major advances in materials must be achieved before the future of MHD Power generation can be predicted.

4. Nuclear fueled steam electric plants--The principal advantage of nuclear fuel is its tremendous energy density. One ton of uranium has the energy potential of three million tons of coals. Present-day reactors convert only about 0.5% of this energy to usable heat, i.e., combustion efficiency is 0.5%. Advanced reactor design, i.e., breeder types, will convert much more energy into a useful form. However, while advanced designs will improve fuel consumption, they will not necessarily increase the thermal efficiency to reduce waste heat in steam-electric plant operation.

   Reduction of waste heat output from nuclear plants will depend on development of advanced converters which will allow higher operating temperatures. Such converters will employ a reactor coolant other than water in the primary flow loop, which circulates fluid through the reactor core for heat absorbtion. The heat is then transferred to steam through a heat exchange process in a steam generator. Systems of this type, still in developmental stages, are using fluids such as helium, liquid sodium or liquid potassium for coolants. Reactor outlet temperatures of over 1000°F are possible.

Because of the vast energy stores in nuclear fuel, its utilization for power production is inevitable. For the next 15 to 20 years, the number of plants in the 30% efficiency class will increase rapidly, which indicates that more efficient systems will surely lag behind our demands for power. This being the case, our immediate efforts must focus on waste heat utilization and dissipation while technology is being developed for more efficient power production methods.

C Waste Heat Energy Utilization

The optimum solution to problems associated with waste heat disposal would be the use of rejected heat for beneficial purposes. When dealing with power plant discharges, however, one is confronted with immense quantities of water which are of low quality when considered as a heat source. Utilization of waste heat in this form is therefore restricted to only a very few possible applications.

1 Agriculture--one potential for such utilization is the farming of plants or animals in fresh or salt water. This has already been successfully practiced in Japan and elsewhere. Heated discharges are used to enhance the environment and increase production of commercially valuable species such as pompano, catfish, shrimp, oysters, and scallops. Research, development, and pilot studies are in progress to determine the feasibility of such cultivation in American waters.

Heated discharges may have application in irrigating and creating controlled environments for agricultural crops. In this manner, growing seasons could be lengthened in certain areas for common crops, and subtropical or tropical varieties might be produced where they are not normally adaptable.

2 Commercial shipping--some nuclear plants could possibly be located to provide beneficial use of heated discharges in keeping shipping lanes free from ice for extended seasons. The recommendation for such application to the St. Lawrence Seaway has been proposed to extend the shipping season to the end of December or even January.

3 Recreation--cooling water may provide heat to warm swimming areas. Such use should be guided by the National Technical Advisory Committee on Water Quality Criteria which recommends: "In primary contact recreation waters, except where caused by natural conditions, maximum water temperature should not exceed 30° C (85° F).

4 Industrial utilization--perhaps the most logical use for the waste heat is to plan for its conversion into an inexpensive energy source for satellite industries that will be constructed simultaneously with the power plant.

When there is no longer any question that the waste heat cannot be put into the nearest body of water, then our American industrial ingenuity will certainly solve the problem of turning this waste heat into an economic asset that can be sold, rather than spend millions of dollars for cooling towers just to get rid of it.

Our industries are based on the use of energy; vast sums of money are spent for it. Why not surround the power plant with new industry and bring about the development of nuclear--industrial parks? Why not computerize the planning of entire industrial complexes based on a nuclear power center instead of our present disorganized approach to industrial siting? We may stand on the brink of a modern industrial revolution which could be triggered by the absurd fact that fish can't stand heat.

D Alternative methods to thermal discharge or waste heat utilization.

There are several methods providing air-water contact for removal of waste heat from water through evaporation and/or conduction-convection. As water is vaporized, heat is consumed at the rate of approximately 1000 BTU per pound of water evaporated. About 75% of heat loss from cooling is accomplished through evaporation. The remainder is accomplished through conduction-convection losses.

The different types of cooling devices now being utilized include the following:

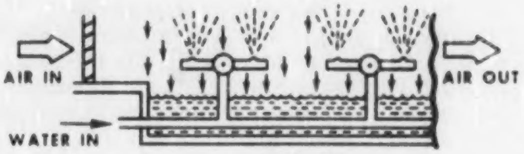
1 Cooling ponds--the cooling pond is the simplest and most economical method of water-cooling (assuming land is inexpensive and available); however, it is also the most inefficient. It may be constructed simply by erecting an earth dike 6 to 8 feet high and may operate for extended periods with no makeup water.

Its main disadvantages are the low heat-transfer rate and the large areas required. For a still pond, the heat dissipated averages 3.5 BTU/hr/ft^2 surface/degree temperature difference between pond surface and air.

2 Spray ponds--cooling can be accelerated in a pond by introducing the warm water through a spray system located 6 to 8 feet above the water surface. Such a system may reduce the required pond surface area by a factor of 20 through increased cooling efficiency. This advantageous savings in land area may be negated through spray system cost, pumping costs, and increased water loss with its associated problems.

Spray ponds may handle as much as 120,000 gpm of water and their low head requirements result in lower pumping costs than for cooling towers.

Performance is limited, however, by the relatively short contact time of air and water spray. Also, impurities may easily enter the system. Properly designed spray ponds may produce overall cooling efficiencies up to 60%. (Figure 1)



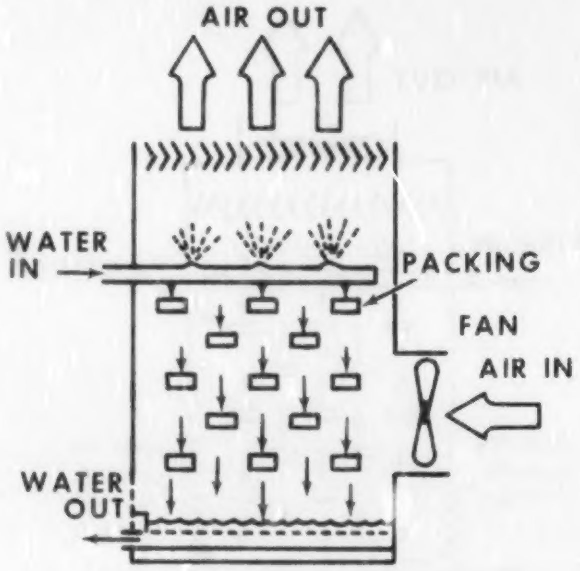
SPRAY POND

FIGURE 1

3 Cooling towers--the terminology applied to the many versions of cooling towers stems from basic differences in design or operation which serve to categorize the types.

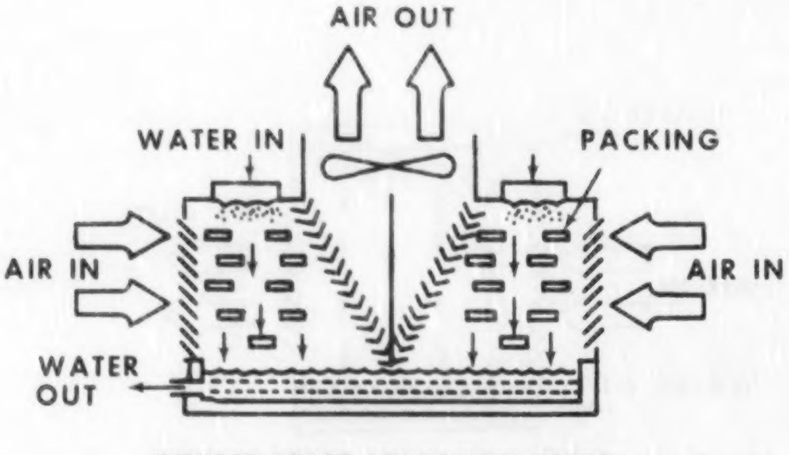
A tower may be either "wet or "dry," depending on whether water is exposed directly to the air; "natural draft" or "mechanical draft," depending on whether fans are employed for air movement; "cross-flow" or "counter-flow," depending on horizontal or vertical air flow through the heat transfer section of the tower. In mechanical draft towers, air flow can be either "forced," i.e., pushed through by fan on bottom, or "induced," i.e., pulled through by fan on top. See Figures 2, 3, 4, 5, 6, 7, and 8 illustrating these different types of cooling towers.

a Mechanical draft towers --as implied, the mechanical draft tower utilizes fans to move the air through the tower. Thus no dependence is placed on natural draft, or wind velocity. The arrangement of the fans dictates the method in which the air is moved through the system, each arrangement having certain advantages and disadvantages.



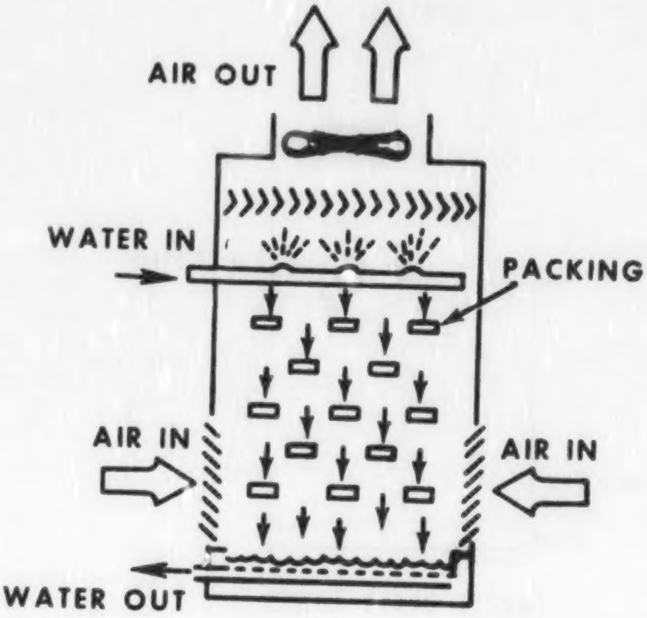
FORCED DRAFT TOWER

FIGURE 2



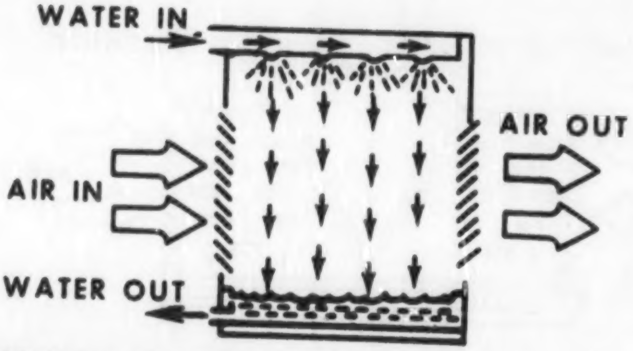
INDUCED DRAFT CROSSFLOW TOWER

FIGURE 3



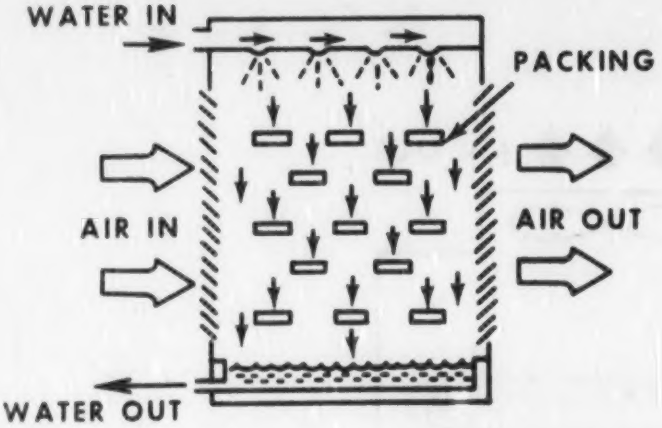
INDUCED DRAFT COUNTERFLOW TOWER

FIGURE 4



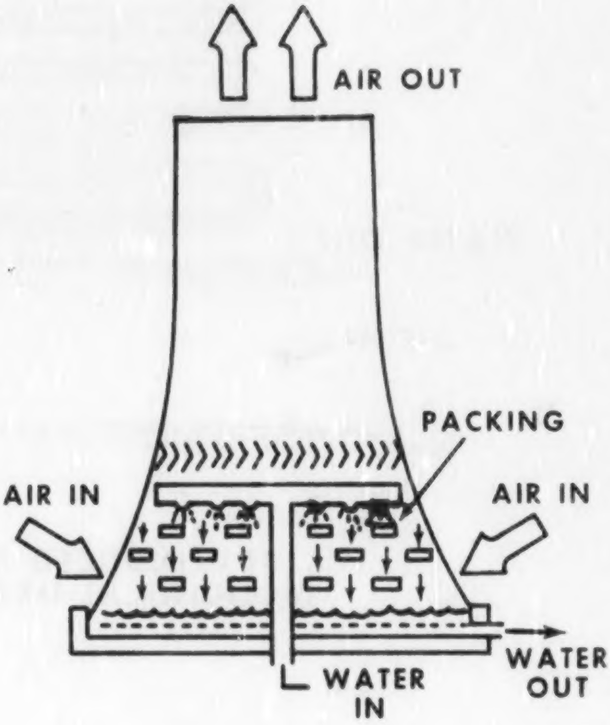
SPRAY-FILLED NATURAL DRAFT CROSSFLOW TOWER

FIGURE 5



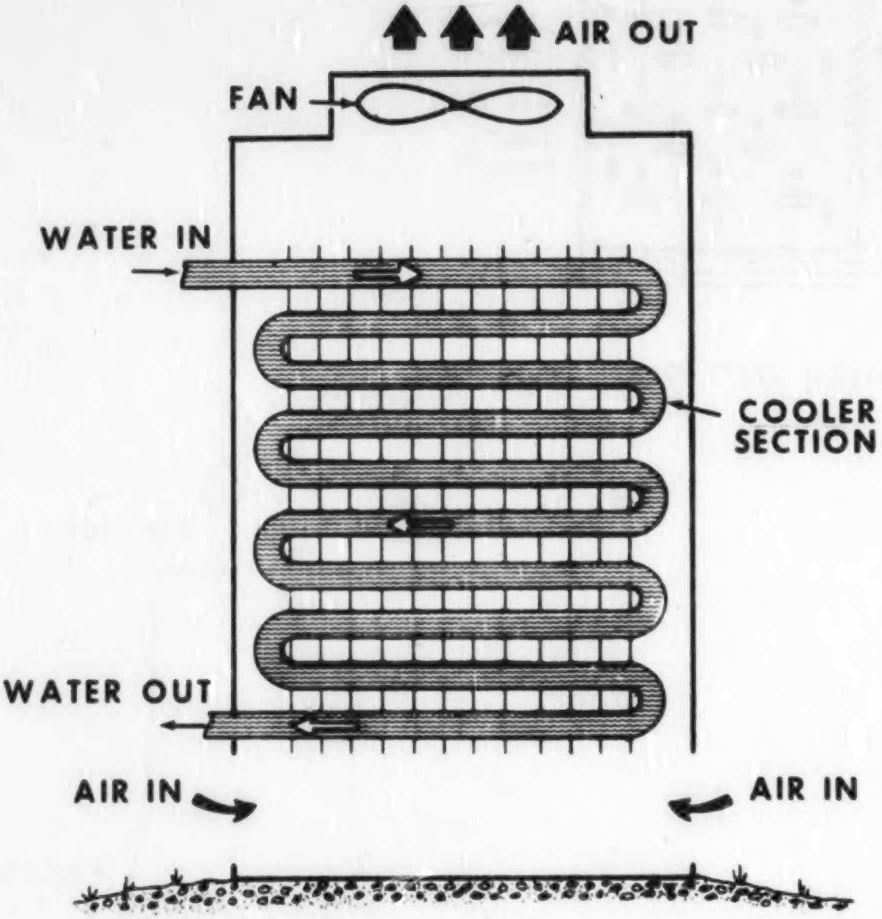
PACKED NATURAL DRAFT CROSSFLOW TOWER

FIGURE 6



HYPERBOLIC TOWER

FIGURE 7



DRY, INDUCED AIR FLOW MECHANICAL-DRAFT TOWER

FIGURE 8

b Natural draft or atmospheric towers--an atmospheric tower implies that air movement through the tower is only dependent on atmospheric conditions. A spray-filled tower depends solely on spray nozzles for increasing the air-water interface, while the packed tower sprays the water over filling or packing. The packed tower is no longer common, however.

Atmospheric spray towers are of the simplest design and may cool up to 1.5 gpm of water per square foot of active horizontal area with the wind blowing at 5 MPH (Marks, 1963). Their advantages include no mechanical parts, low maintenance costs, no subjectivity to recirculation of used air, and long, trouble-free life.

Disadvantages include high initial cost (approximately identical to a mechanical-draft tower), high pumping head, location in an unobstructed area, required great length because of rather narrow construction, high wind losses, and nozzle clogging. This design is well suited for small operations, however.

c The chimney or hyperbolic towers--the hyperbolic tower operates similar to a huge chimney: the heavier outside air enters at the tower base, displaces the lighter, saturated air in the tower, and forces it out the top. The initial cost is higher, but it is balanced against savings in power, longer life, and less maintenance. Their operation is countercurrent, they can cope with large water loads, and they require a relatively small area.

These towers will probably become common in the United States as the cooling-tower requirements expand.

d The dry-cooling tower--the dry-cooling tower is not an evaporative cooling device; instead, it cools fluids by forcing or inducing atmospheric air across a coiled cross-section. They eliminate water problems, such as availability, chemical treatment, water pollution, and spray nuisance; and there is no upper limit to which air can be heated.

However, the dry-cooling tower is much less economical than an evaporative cooling device, the specific heat of air is only one fourth that of water, and maintenance costs are high.

Thus, the cost of dry-cooling towers is presently thought to be prohibitive for most installations, even though many conservationists believe these are the only answer to the thermal-pollution problem.

III FIELD CONTROL METHODS

A Logging Operations--measurements of summer temperatures in small streams flowing through logged and unlogged forest areas show water temperature increases of 14-16° F in the unprotected stream. Temperature increases of this magnitude produce stream temperatures which are far in excess of optimum and are even in the range of temperatures known to be damaging to resident and anadromous fish which spawn, grow, and migrate in the small forest streams. Such increased temperatures make possible the rapid growth of trash fish, slime bacteria, and algae.

Soil erosion on, and logging debris from, roads, landings, skidways, and slopes disturbed by yarding activities during a logging operation can also seriously affect streams. Much of this damage can be prevented by using all reasonable means and alternatives that will keep every road and logging activity as far from the stream courses as possible.

B Agriculture--clearing of fields to the water's edge exposes the stream to the full impact of heating by the sun with resulting increases in water temperatures.

Therefore, leave buffer strips of native vegetation, including an overhead canopy, between cleared fields and any perennial streams they parallel. Buffer strips not only reduce the quantity of sediment and pesticide and fertilizer drainage that reach the streams, but also help prevent stream water temperature increases and loss of natural stream beauty. Thus, they assist with the preservation of water quality and the attainment of temperature objectives for fish management.

IV SUMMARY

We see that there are methods available for reducing or controlling thermal pollution through process changes and the development of new methods of power generation. The advances that have been made, however, have been slow in coming. Waste heat utilization, therefore, takes on more and more importance as it is obvious that water quality standards set for interstate streams and coastal waters can only be expected to become more stringent in the future.

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